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Mold Modeling of Metallic Tension Bar in AA 7075 Aluminium Alloy Casting

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1. Introduction

The aluminium and its alloys are used in various casting-forging forming works and at heat treatment conditions. It has been taking place in the metal market along with the iron and steel for more than 70 years. The ever-increasing demand of aluminium has been gaining stream due to combination of its unique properties and this has become one of most versatile properties of engineering and construction materials [1]. The distinct metal which abounds subsequent to the iron is the aluminium. It is the second biggest metal of engineering materials [2]. The aluminium alloys which are mostly preferred in the applications besides the pure aluminium are very attractive due to their low densities, property of being solidified by precipitation, good corrosion resistance, high thermal and electrical conductivity and high damping capacity [3]. Due to their high mechanical properties, 7xxx alloys are widely used within the commercial aluminium alloys in the fields of aviation, automotive, sport materials and other areas because of its high resistance and hardness, good corrosion resistance and perfect weld ability [4]. Especially, AA 7075 aluminium alloys may be obtained with high hardness and resistance by alloying zinc, copper and magnesium in the commercial aluminium alloys [5]. The extremely high resistant 7075 aluminium alloys also find place in the manufacturing technologies of aero structures, gears, shafts and other various commercial aircrafts, aerospace-spacecrafts and transportation vehicles [6]. In order to meet the increasing demands of afore-mentioned systems, the manufacture of large scaled Al-Zn-Mg-Cu alloyed ingot castings which are high resistant and have high ductility and high abrasion resistance have importance in the recent years [7]. In general, AA 7075 aluminium alloy is simple and economic due to the possibility of using conventional casting equipment to produce without any limitation in terms of casting methods and the sizes and shapes of components [8].

The permanent die casting technology mostly takes place among the casting process options for aluminium alloys [9]. The permanent molds used in molding the aluminium alloys typically include a wide range of materials from a gray cast iron to high resistant tool steel. The general failure reasons for permanent molds may be defined as the thermal fatigue crack revealed by the repetitive thermal tensions at mold surface. The resistance against the thermal fatigue may be increased with the mold materials which have the combination of high thermal conductivity, high resistance at high temperatures, low thermal expansion coefficient and low elasticity modulus. The studies have continued to be conducted to increase the quality and extend the lifetime of permanent molds used in the aluminium casting.

The gray cast iron, ductile iron, casting and forging 4140 type steels or H13 type steels may be preferred for mold material at typical thermal conditions and lifetime [10]. In general, the tensile test bars may be produced apart from the procedure itself (salt or permanent mold) to assess the metal quality of molten liquid metal in the production made with casting technology [9]. ASTM B108 standard mold design is widely used for industrial cast test bar specimens. Besides that, this mold design is valid for permanent mold casting technology with the effect of permanent. In the recent years, the demand for use of permanent mold technology has been gradually increasing [11]. The programs such as cast modeling and analysis, etc. is very significant in terms of faultless casting practices with the design in computer environment without feeling a need for producing unnecessary and faulty casting with trial and error method. The control of casting conditions such as temperature of alloy casting, period for filling the mold by liquid metal, etc. take place among the significant parameters in the casting practices [12]. In last twenty years, the design of casting processes and their optimization in terms of quality have been substantially increased in parallel with the casting design modelling and use of analysis software. Today, the production design, modelling and analyses of castings in most foundries are firstly made in the computer environment and thereby, the failure rate is minimized [13].

In this paper, the permanent mold was produced following thermal stress, fatigue life and damage analyses with the permanent mold technology, tensile test bar mold design, modelling and analysis studies in the casting of Al alloys. The microstructure and mechanical properties of AA 7075 aluminium alloy after melting and casting process were examined.

2. Experimental

Redesign of the tensile test bar mold defined as ASTM B108 [14] standard in metallic mold casting practices was realised. Redesign metallic mold was used for a single metal tensile test bar production (Fig. 1) and then to optimize the mold with modelling and analysis studies. At the same time, it was also aimed to produce AA 7075 aluminium alloy as convenient for casting and faultless casting part which takes place in the aviation, defense, automobile industry and engineering practices and which is used in the experimental studies. Before the permanent mold casting practices, the modelling and optimization studies were conducted by using a computer aided program for design and analysis practices with the aim of not creating any casting failure resulted from the mold either in the industrial or experimental studies conducted on tensile test bar.

In terms of casting experiments and properties of produced to be obtained, the thermal stress, fatigue, damage and liquid metal flow analyses were applied on the mold designed under preheating parameter in the virtual environment.

The preheating temperature of casting mold which is a significant parameter in the casting practices was used as 100°C, 150°C and 200°C in the modelling studies. AA 7075 aluminium alloy was studied either during design and analyses or in the casting practices.

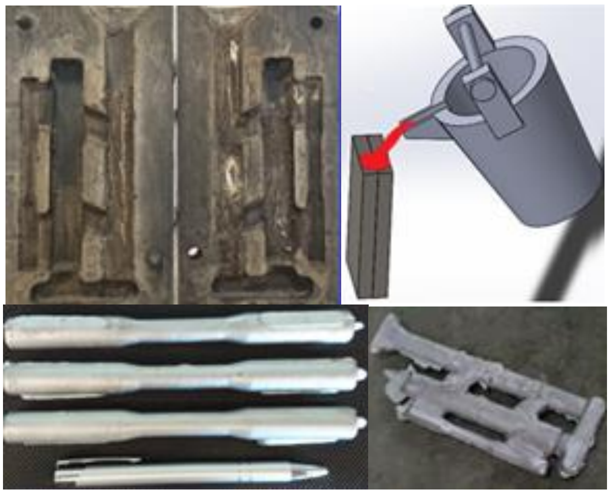


Fig. 1 Metallic mold design and tensile test bars after casting

This mold produced following its design and analyses by aiming at a single tensile test bar production was manufactured from H13 (X40CrMoV5-1) hot work tools steel. The metallic mold casting procedures of aluminium alloy stated were conducted by melting at resistance melting furnace at 800°C. With the aim of determining the chemical composition of AA 7075 aluminium alloy melted and casted, the spectral analysis was conducted before the casting procedures (Table 1).

Table 1

The chemical composition of AA 7075 alloy

Al	Si	Fe	Cu	Mn
89.10	0.37	0.38	1.70	0.17
Mg	Zn	Ni	Cr	Ti
2.56	5.40	0.01	0.16	0.02

The spectral analysis practices were conducted by using spectralab brand M5 model analyzer. The metallic tensile bars of AA 7075 aluminium alloy obtained after the melting and casting practices were prepared in accordance with the metallic tensile bar sizes given in Table 2 and tensile bar specimen given in Fig. 2. The tensile tests of experiment specimens were conducted with DARTEC brand M9000 model 600 kN Universal Test equipment pursuant to TS EN ISO 6892-1 standards. The post-melting and post-casting hardness measurements of aluminium alloy were conducted with REICHERTER brand BL 3 model test device pursuant to TS 139-1 EN ISO 6506-1 0 standards. The hardness measurements of experiment specimens were conducted by applying 0.5 mm2 ballpoint and 500 kg load.

The general metallographic studies were conducted in terms of microstructural characterization of aluminium alloy melted and casted. The casting aluminium alloy was etched with Keller solution (0.5 HF-1.5HCl-2.5HNO3-95.5 H2O) following the grinding and polishing procedures, respectively. The Leica optical microscope was used in the experimental studies with the aim of determining the micro structural transformations of cast aluminium alloy and the fracture surface morphologies of experiment specimens that they demonstrated following the tensile test experiments

Table 2

Measurements of tensile test bars produced

Test specimen diameter *d*0 (mm)	The diameter of the head *d*1 (mm)	Length of the head *h* (mm)
10	M18x2.5	25
The length of the thinned part *Lc* (mm)	Total length *Lt* (mm)	Curvature radius *R* min
60	110	10
	First dimension length *Lo* (mm)	
	50	

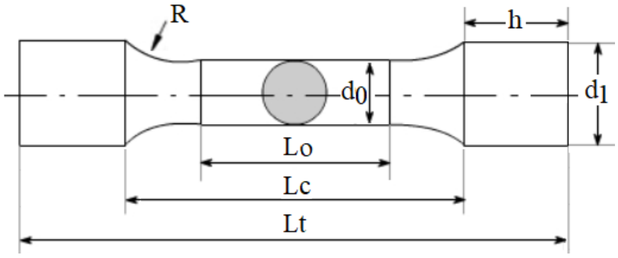


Fig. 2 Tensile test bar

3. Results and discussion

The metallic mold design was made by aiming at a single tensile test bar to use in the modelling and analyses of cast mold before the practices of melting and casting in the permanent mold (Fig. 3).

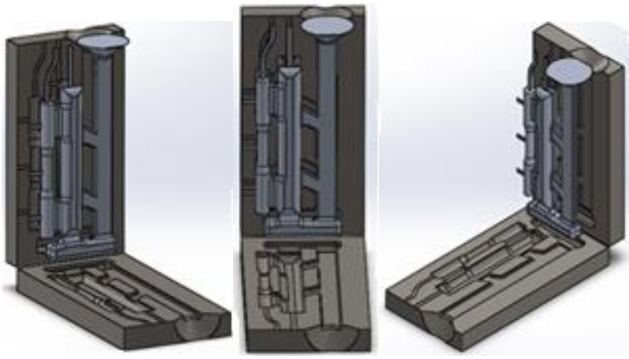


Fig. 3 Permanent mold design

The mass properties of metal tensile bar mold designed before the stage of melting and casting in permanent mold were determined to be used in the modelling and analyses studies. The properties of permanent mold determined are given in Table 3. The mathematical model mesh image of mold which constitutes a significant phase in terms of mold design and analyses used in the permanent mold modelling (CAD model) and finite elements analyses of AA 7075 aluminium alloy, is given in Fig. 4.

Table 3

Mass properties of permanent mold

Thermal conductivity W/(m.K)	Specific heat J(kg.K)	Mass intensity Kg/m^3	Casting Temp. ^oC	Permanent mould material
24.3	460	7800	800	H13

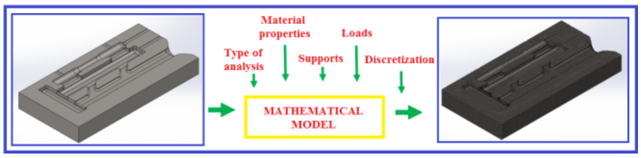


Fig. 4 Permanent mold and mathematical model mesh Image

In the permanent mold casting technology practices, the preheat of mold is a significant parameter in the sense that the liquid metal may fill the mold in a more effective and efficient way following the melting procedure and before the casting stage [11]. In this regard, the finite elements analyses conducted at 800°C casting temperature and 100, 150 and 200°C preheating temperatures are shown in Figs. 5, 7 and 9, respectively. As seen on the mold given in Fig. 5, the thermal stress distributions on the permanent mold surface were evaluated in terms of four regions individually depending on the preheating parameter of mold. These regions were examined in the modelling and analysis studies before the casting experiments as follows: the first region where the tensile bar was located (a-b-c), the second region where the riser was located (d), the third region as the horizontal runner (e) and finally the fourth region where the vertical runner (f) was located (Figs. 5-7-9).

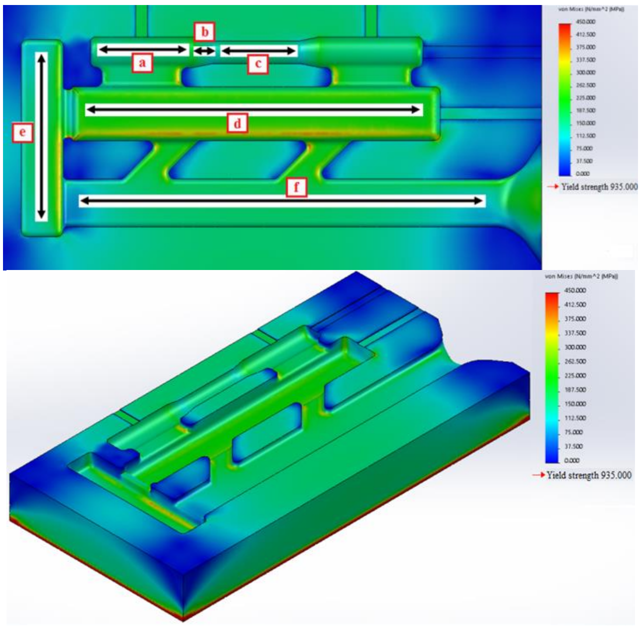


Fig. 5 Predicted thermal stress image of permanent mold pre-heated at 100°C

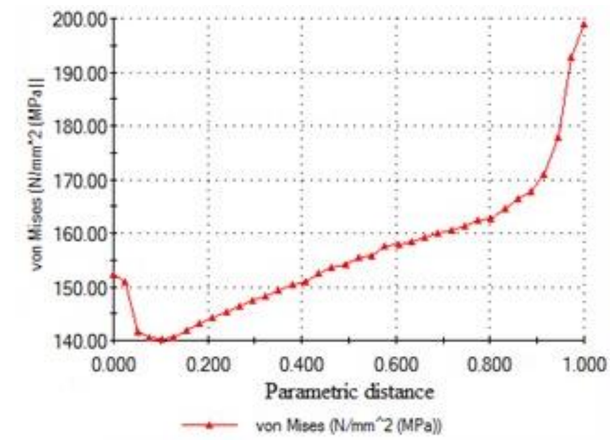
The thermal stress distribution analysis results of regions stated in the permanent mold runner and riser design are shown in Figs. 6, 8 and 10, respectively. In the permanent mold design, the thermal surface stresses were graphed with the examination of mesh elements on the line drawn with the finite elements model on the surface in the regions of a, b, c, d, e and f (Figs. 6, 8 and 10). In these graphics, the surface stress under the influence of preheating at 100°C, 150°C and 200°C were determined to be at the range of 150-200MPa, 250-330MPa and 350-470MPa along the line of a region received from the tensile bar. In the region of b received from the tensile bar, this was determined to be at the range of 200-110MPa, 330-190MPa and 475-275MPa (100°C, 150°C and 200°C), respectively depending on the increasing preheating temperature.

The thermal surface stress along the line in the region of (c) which was defined as the measurement size on the tensile bar [15] was determined to be averagely 150MPa, 250MPa and 350MPa, respectively with the increase of three preheating temperatures (100°C, 150°C and 200°C). It is a significant result that the yield strength (935MPa) point was not exceeded in the linear static elastic region finite elements numerical calculation of pre stresses at preheating in order to cast the tensile bar faultlessly and healthily with the permanent mold technology. The safety factor was approximately 2 by proportioning the yield strength to the value (400MPa) at which thermal stress intensified at 200°C. At the riser region (d) that was another significant region, the average thermal stress values were determined to be 225MPa, 380MPa and 530MPa, respectively depending on the increasing preheating temperature applied to the permanent mold (100°C, 150°C and 200°C). The highest thermal stress value was observed as 530MPa in this region at 200°C preheating temperature. In the same way, the change of average thermal stress values under the influence of increasing preheating temperature were determined to be 180MPa, 300MPa and 420Mpa at the horizontal runner region (e) and 170MPa, 275MPa and 400 MPa at the vertical runner region (f).

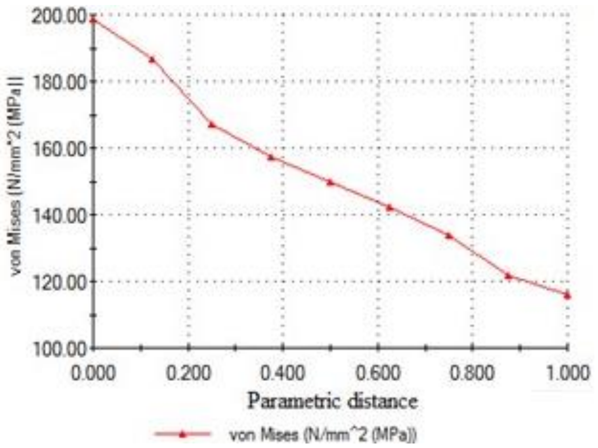
The fatigue analyses of AA 7075 aluminium alloy were conducted with finite elements method, Goodman fatigue theory and Van Misses tensile stress methods at the final stage of modelling and analysis studies before the casting experiments (Fig. 12, 13). In the analyses made, the fatigue S-N data of H13 tool steel were used (Fig. 11). As a result of analyses made, the damage lifetime percent in the second region (d) where the riser took place and the lifetime cycles occurred in this region were revealed in the mold design at which especially thermal stress intensified (Fig. 14).

As a result of lifetime cycles obtained in the second region at which the riser took place, it was determined that the permanent mold had a lifetime approximately at the range of 95.000-100.000 (Fig. 14).

The fatigue lifetime which is significant in the permanent mold technology determines the service life of mold. At this point, the significant issue is the optimization of heat increase which leads to increase of thermal stresses. This optimization is so significant that the heat shall be both low enough not to decrease the lifetime and high enough to minimize the internal stresses at the part casted.



a



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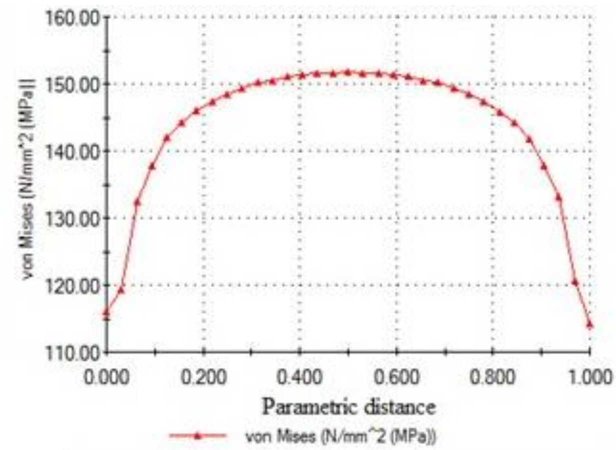
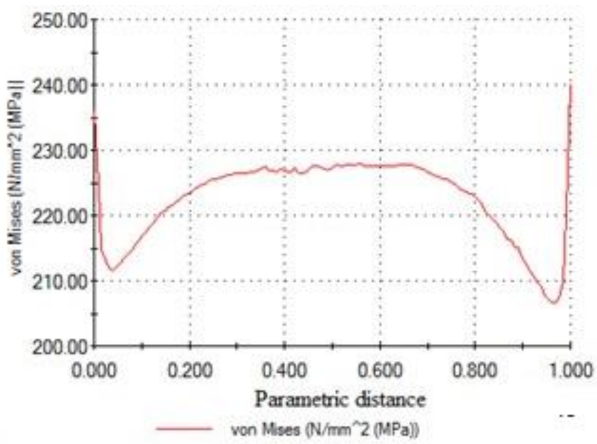
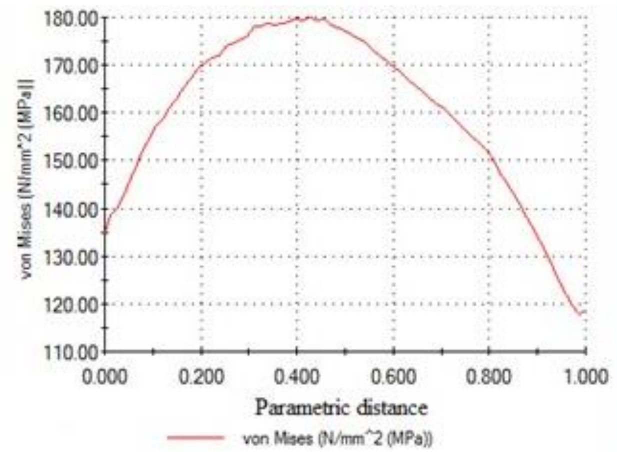


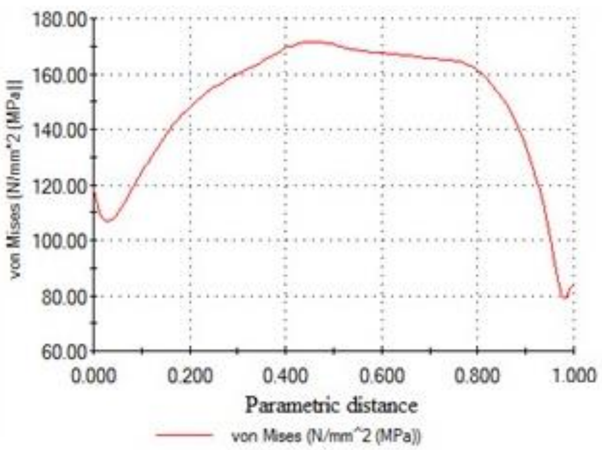
c



d



e



f

Fig. 6 Predicted thermal stress analysis results of permanent mold pre-heated at 100°; (a)-(b)-(c) tension bar area, (d) riser, (e)-(f) horizontal and vertical runner

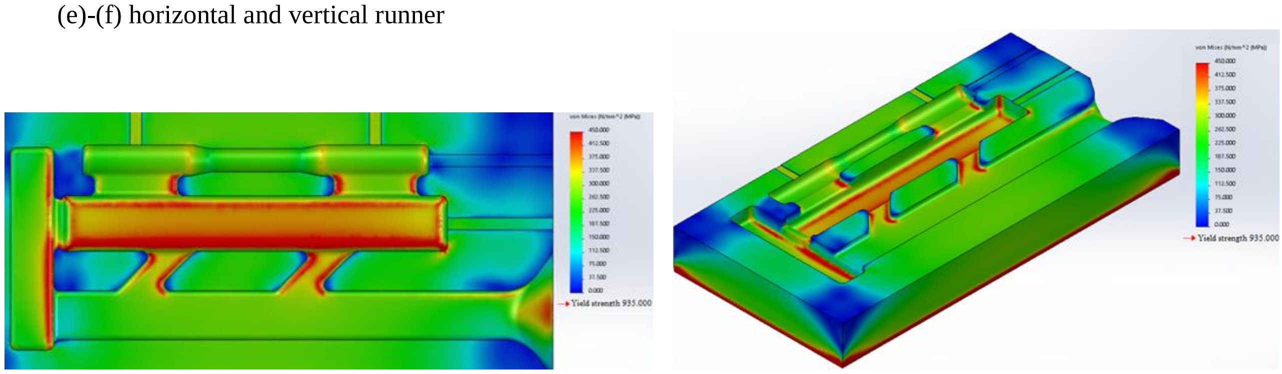


Fig. 7 Predicted thermal stress image of permanent mold pre-heated at 150°C

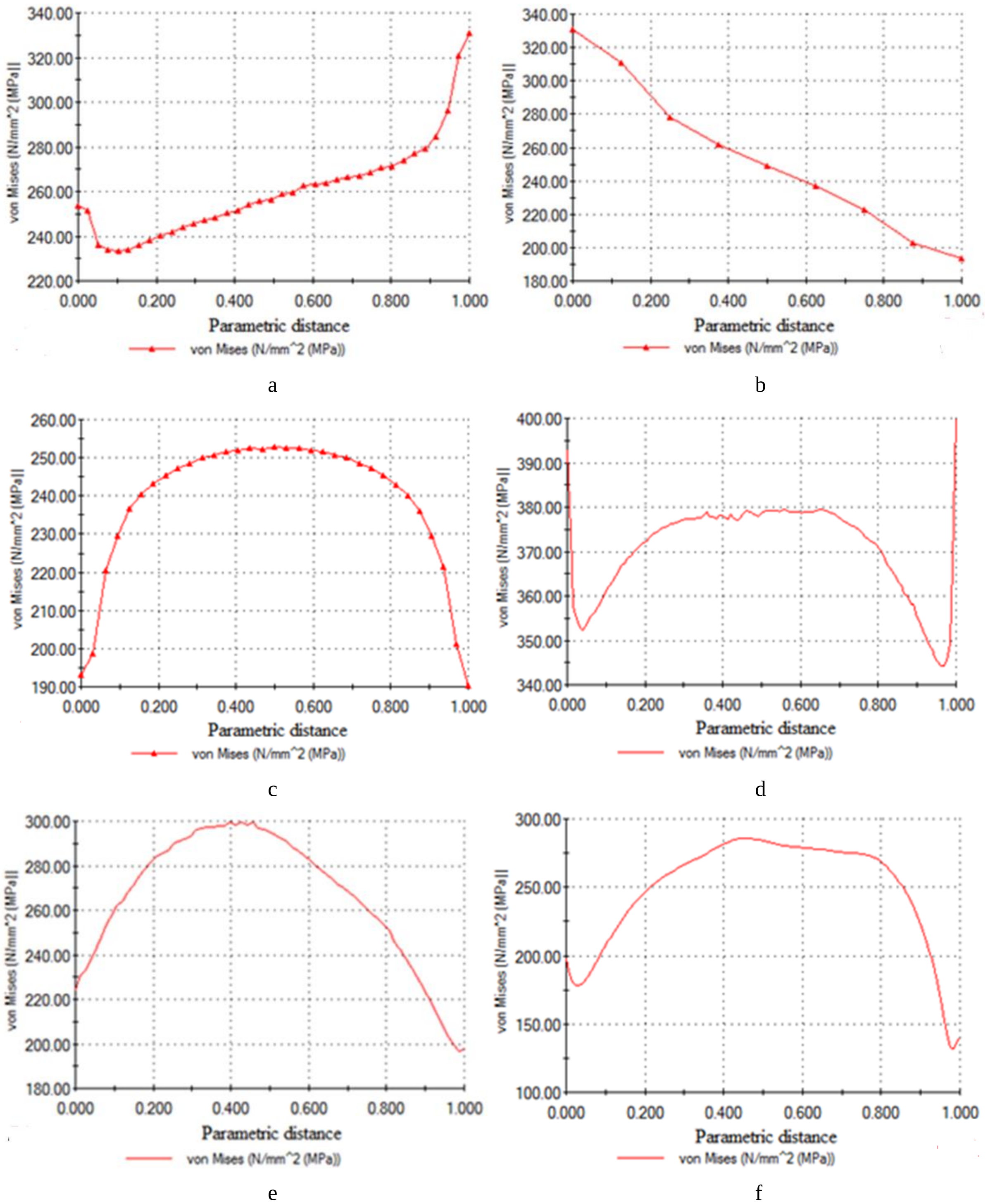


Fig. 8 Predicted thermal stress analysis results of permanent mold pre-heated at 150°C; (a)-(b)-(c) tension bar area, (d) riser, (e)-(f) horizontal and vertical runner

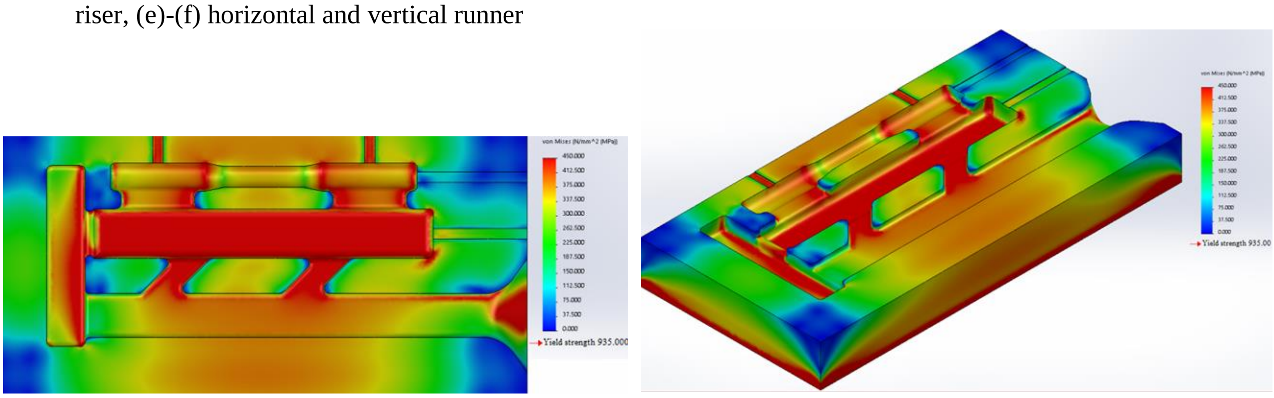


Fig. 9 Predicted thermal stress image of permanent mold mold pre-heated at 200°C

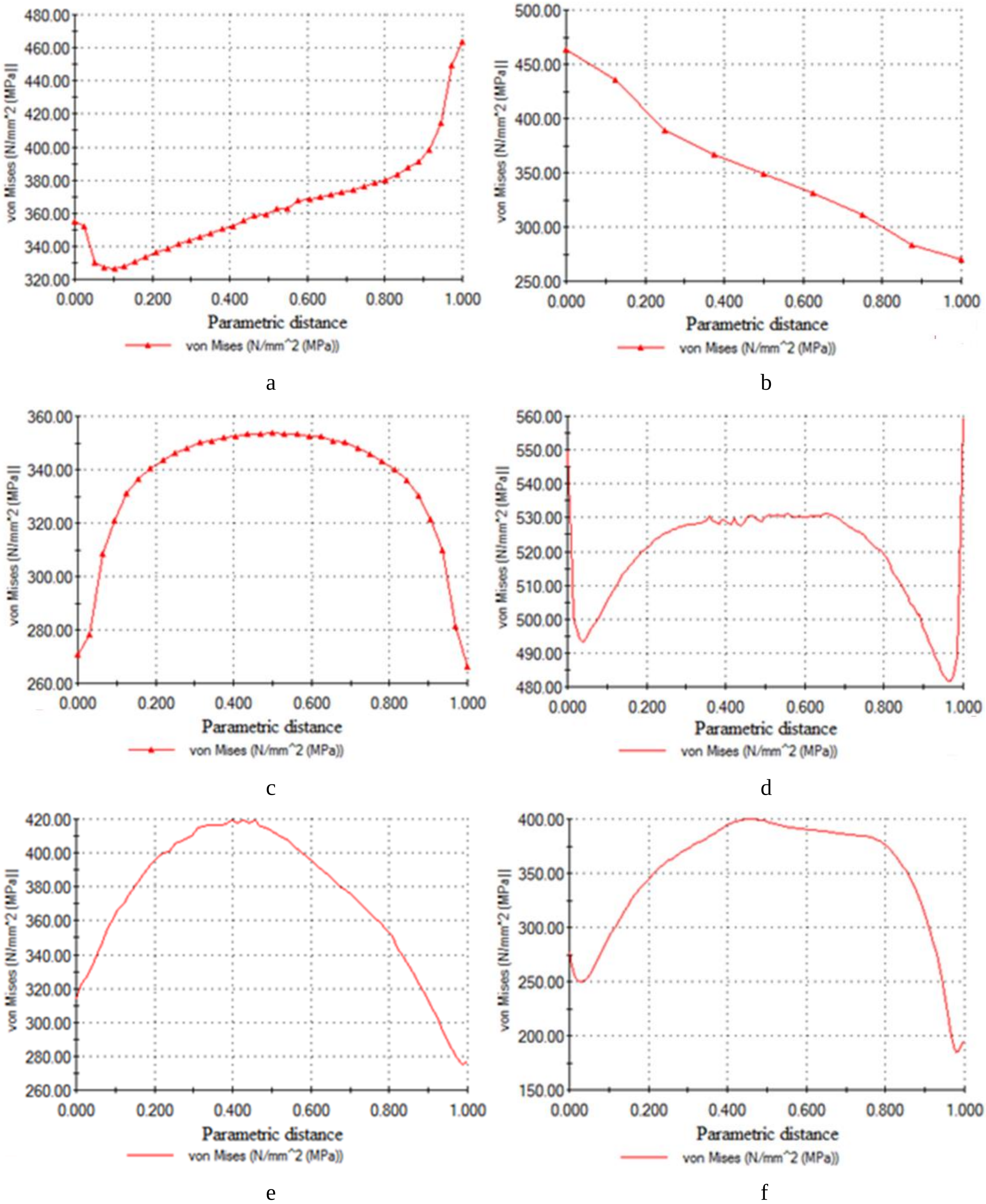


Fig. 10 Predicted thermal stress analysis results of permanent mold pre-heated at 200°C; a-b-c – tension bar area, d – riser, e-f – horizontal and vertical runner

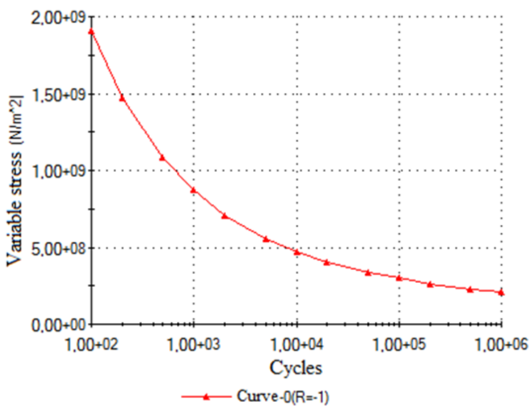


Fig. 11 S-N curve

Within the direction of literature reviews made on the permanent mold casting technology, it was stated that the lifetime of permanent molds are convenient up to 100.000 casting with the casting procedures experimentally made following the melting procedure [12]. The analysis results obtained revealed that this mold designed and modelled yielded similar results. In conclusion, the thermal stress values occurred at mold under the preheating and the mold lifetime at casting temperature (800°C) may be calculated with the finite elements method. In this way, the optimum mold design and modelling made in this study at casting temperature (800°C) stated may make significant contribution in the permanent mold casting technology.

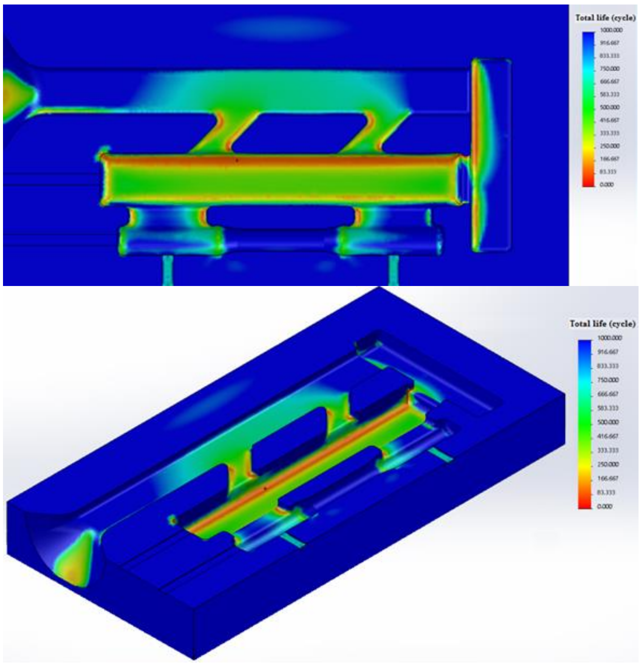


Fig. 12 Predicted fatigue damage percentage image of permanent mold at 800°C

This mathematical method applied instead of expensive experimental methods may be used before the casting experiments or practices with regard that they may find an alternative place effectively and efficient in the permanent mold casting technology of aluminium, light alloys, etc.

Thanks to this method, it may be got to the stage of manufacturing at minimum risk after designing convenient mold temperature and geometry before getting to the manufacturing stage. After the modelling and analysis studies, the casting simulation studies were also conducted in terms of permanent mold filling (as vectorial) and solidification time of AA 7075 aluminium alloy (Figs. 15, 16).

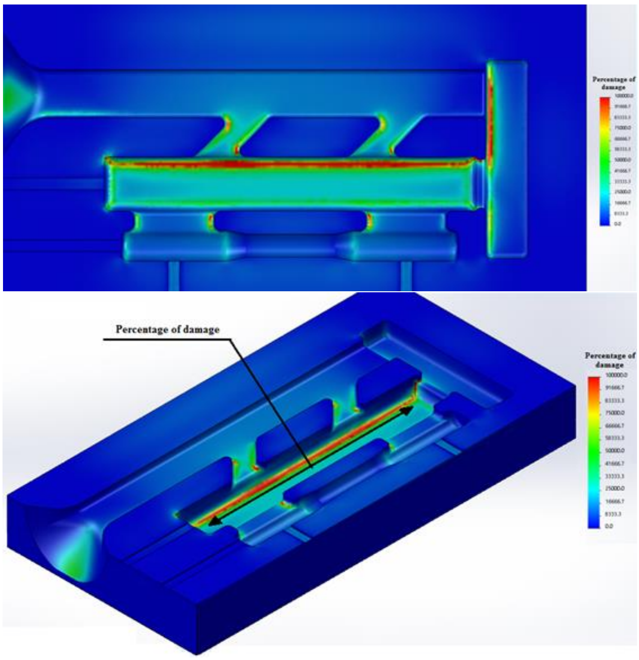


Fig. 13 Predicted percentage of regional damage image in riser at 800°C

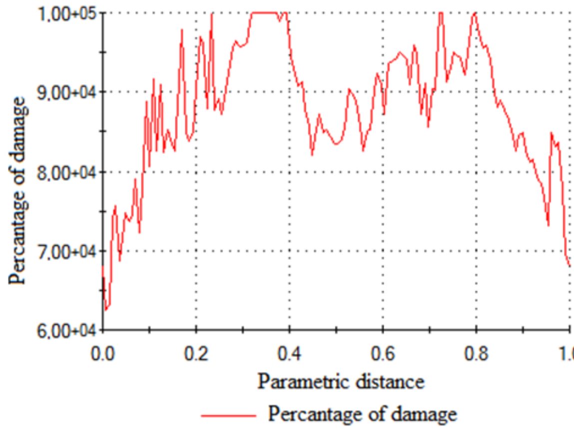


Fig. 14 Percentage of regional damage curve in riser at 800°C

Fig. 15 Vectorial filling analysis degrees in permanent mold of AA 7075 alloy

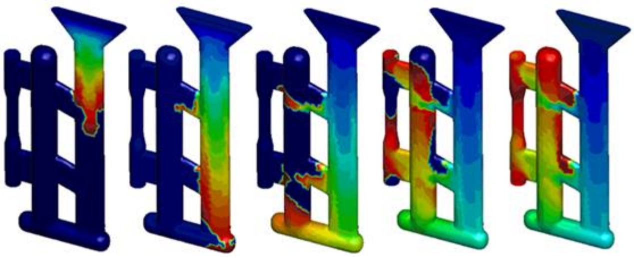


Fig. 16 Solidification analysis degrees in permanent mold of AA 7075 alloy

As a result of modelling and analysis studies, the microstructure images of cast aluminium alloy following the melting of AA 7075 aluminium alloy at 800°C and casting experiments in the permanent mold are given in Fig. 17. The rose and spherical primary α (Al) particles were determined in terms of microstructure formation [5, 16, 17]. From Fig. 17, we can see microstructures at different magnifications microstructure images of AA 7075 aluminium alloy after casting process (800°C-prehetaed at 100°C). Due to preheating after casting, the heterogeneity did not unformed in the center and external zone of microstructure. Mostly the microstructure was obtained as equiaxed grain structure.

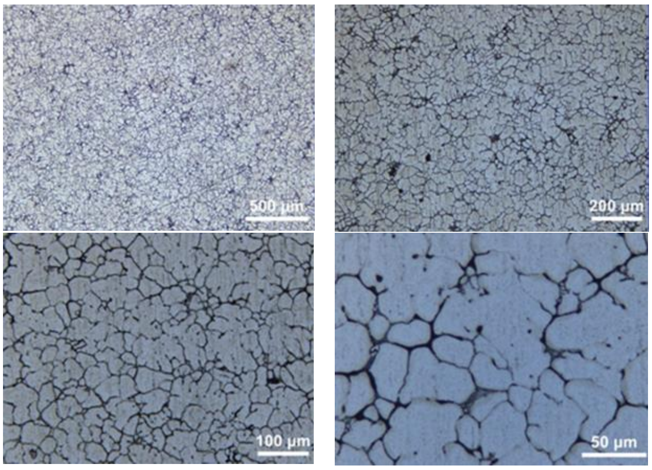


Fig. 17 Micro structure images of AA 7075 aluminium alloy

At the end of melting at 800°C and casting experiments made in the permanent mold, the mechanical properties results of AA 7075 aluminium alloy (tensile strength and hardness) obtained after the micro structural examination studies are shown in Table 4.

When the mechanical property results given in Table 4 are reviewed, it is seen that the tensile strength and percentage elongation of metal tensile bars obtained after the casting experiments of AA 7075 were determined to be 7 and 125.9 N/mm^2, respectively. When the hardness results of aluminium alloy casted (Table 4) are reviewed, it is seen that it had the hardness value of 80HB.

In the permanent mold practices made, the mechanical properties of parts casted are as significant as the lifetime of mold in terms of manufacturing. The heat increase which is a factor decreasing the lifetime of mold may make positive contribution to the mechanical properties

Table 4

The mechanical properties of aluminium alloys after casting process

Alloy	Percentage Elongation (%)	Tensile strength (N/mm^2)	Hardness Value (HB)
7075	7	125.9	80

Therefore, the optimization studies are very significant in the mold design. The simulation studies and conformance tests shall be made for this reason and the cross-correlations shall be evaluated accurately. In this way, the reliability of simulation may be ensured. When the fracture surface morphologies demonstrated by AA 7075 aluminium alloy as a result of tensile test made following the casting experiments applied at the continuance of permanent mold for which design and analysis studies were conducted are reviewed (Fig. 18), the existence of cleavage type fractures were observed instead of dimple fractures generally occurred as a result of progress of stress fractures at ductile fractures [5, 7]. Therefore, fully cleavage type fractures were observed on this alloy demonstrating low ductile value instead of the dimples on the rupture surfaces.

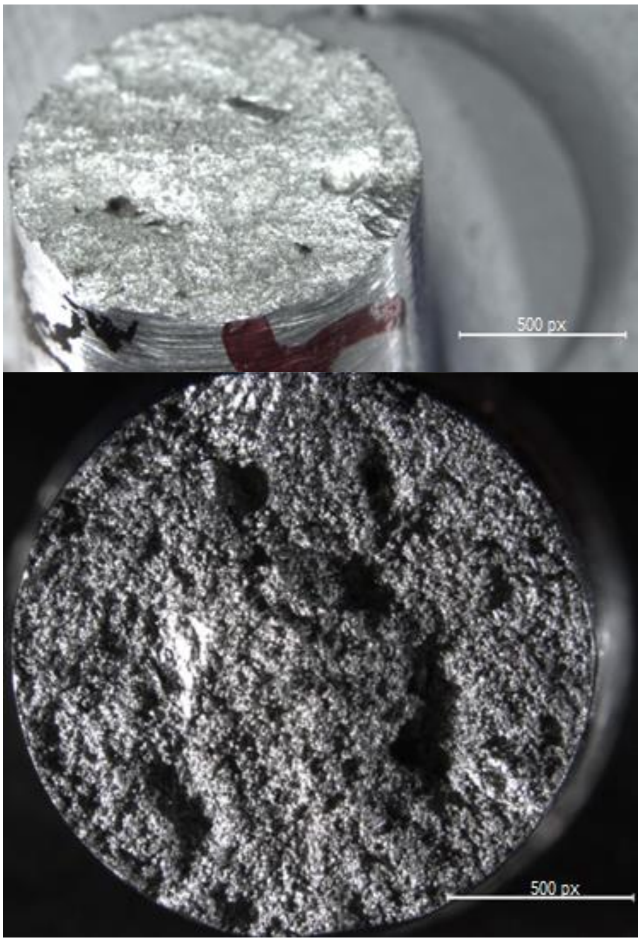


Fig. 18 Fractured surface morphology after tensile test of aluminium alloy

This condition (fracture surface morphology) can be seen more clearly after the AA 7075 aluminium alloy tensile test in SEM image (Fig. 19). AA 7075 aluminium alloy fracture surface studies usually indicate coexistent brittle-ductile fracture zones [18]. From the fracture surface morphology of AA 7075 aluminium alloy in SEM image, mostly brittle fracture zones as well as relatively few ductile fracture zones can be seen.

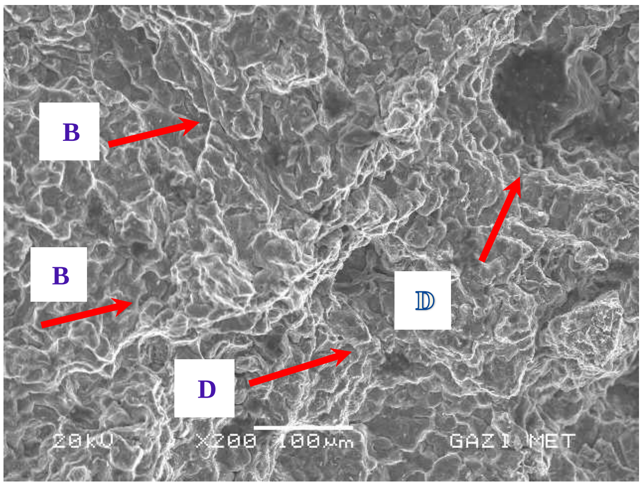


Fig. 19 SEM images of fractured surface after tensile test of aluminium alloy; B: Brittle, D: Ductile

4. Conclusions

Within the scope of permanent mold casting technology which reserves a significant place in the casting technology of light alloys, the results obtained from the casting experiments following the metallic mold design, modelling, analysis and simulation studies are summarized as follows;

In the permanent design, modelling and analyses, it was determined that their thermal stress distributions increased based on increasing preheating temperature selected. It was determined that the mold surface did not expose to any permanent deformation under highest preheating temperature at 200°C in terms of thermal stress distributions. Depending on the increased preheating temperature, the permanent mold service life was tested approximately as 95.000-100.000. At casting temperature at 800°C, it was proven with the numerical calculation that the riser region (d), the second region, was the region which suffered the highest damage in terms of thermal fatigue and this was validated experimentally. After casting of AA 7075 aluminium alloy at 800°C, 80HB hardness value as well as elongation (7%) and tensile strength (125.9 N/mm^2) was measured. After the tensile test, mostly brittle fractures were identified were determined by SEM image. It can be stated that metallic tension bar casting process can be carried out as experimentally and numerically in the mold.

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H. Gökmeşe

MOLD MODELING OF METALLIC TENSION BAR IN AA 7075 ALUMINIUM ALLOY CASTING

S u m m a r y

In this paper, the design and application of permanent mold casting technology reserving a significant place in the light alloy casting technology was conducted due to its convenience for mass production and industrial need. The metal tensile bar mold design, mold preheat temperature (100°C-150°C-200°C), thermal stress, fatigue and damage analyses were examined to be used in the casting experiments by using the finite element analysis. As well as the casting temperature and solidification time, the material flow analyses were conducted by using a computer-aided program. By producing the mold following the modeling and analyses studies, AA7075 aluminum alloy was melted at 800°C and casted in the permanent mold. Following the casting procedure, the tensile bars of aluminum alloys were prepared in conformity with the standards and their tensile and hardness tests were conducted. The general and fracture surface microstructure differences of experiment specimens were examined. As a result of modeling and analysis studies made in the computer environment, the surface stresses of specimen and runner regions which were significant in the mold design were calculated at 100, 150 and 200°C preheating temperatures. The most convenient mold lifetime was calculated by making fatigue calculations for permanent mold at 800°C.

Keywords: casting, permanent mold, aluminium, analysis, mechanical properties.

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