DESIGN OF DIE CASTING METHOD FOR PRODUCTION OF DETAILED WEAPON PARTS UNDER HIGH IMPACT LOADINGS

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ABSTRACT

The presence work is aimed at studying low-cost production of high performance weaponry parts operating under cyclic impact loadings. In order to achieve this goal, die casting technology of non-ferrous alloys is employed with high strength steel inserts. Briefly, Pre-formed steel parts were placed on specially designed die casting molds and non-ferrous metal is injected into the mold. Positions, sizes and shapes of high strength inserts were decided by results of finite element analysis of the service loadings. ZAMAK 7 alloy was used as base alloy for experiments and AISI 303, 1.2379 (D2) steel alloys were preferred for inserts of a dedicated part. Quantitative metallographic porosity investigations were applied and interface chemistry was evaluated via XRD. Produced parts were operated in the real weapon and post examinations were performed.

ÖZET

Bu çalışmada tekrarlı darbe alan, yüksek performans ve düşük ölçü töleransı gerektiren silah parçalarının düşük maliyette üretimi amaçlanmıştır. Bu amaca ulaşmak için yüksek dayanımlı çelik takviyeler ile birlikte basınçlı döküm teknolojisi kullanılmıştır. Kabaca işlem, şekillendirilmiş çelik takviyelerin özel olarak dizayn edilmiş kalıplara yerleştirilmesi ve demir dışı alaşımın kalıba dolmasıyla özetlenebilir. Takviyelerin pozisyonları, boyutları ve şekilleri; servis yüklemelerin simule edildiği sonlu elemanlar analizinden sonra kararlaştırılmıştır. Enjeksiyon metali olarak ZAMAK 7 alaşımı, takviyeler için de AISI 303 ve 1.2379 (D2) deneyler için uygun görülmüştür. Sayısal metalografik porozite ölçümleri yapılmış ve arayüz kimyasının denetlemek için XRD spektroskopisi uygulanmıştır. Bunların yanında üretilen parçalar silahta denenmiş ve incelemeye alınmıştır.

Key Words: Die, Casting, Insert, steel, Zinc

1. INTRODUCTION

Weapon mechanisms should be designed in the way that they should operate in all offensive service conditions without any failure or locking after thousands of cycles. Thus, their mechanism parts are not assembled strictly in order to avoid any tie-ups, which means all parts can freely move in a small limit of freedom. [1] This fact causes working elements are not in touch and they transmit the motion by impacting the next component. In addition to this, firing mechanisms of weapons are continuous cycles which cause another phenomenon called fatigue of components. These two limitations result as need of high strength and toughness which is responded by steels like 32NiCrMo14-5, 14NiCr14 etc. However, Shaping and machining operations are very expensive as much as case hardening, coating and size control steps costs. Moreover, labor cost is remarkably high since shaping and machining operations consist of 30 or more handwork steps.[2] Purpose of this study is to resolve this cost problem and increase production rate without sacrificing durability.

Production method can be explained in four main steps. First step is preparing inserts which consist of shaping and hardening of steel. Inserts do not require near net shaping as the part since most of its faces stay in base metal. However precautions should be taken to fix the insert in the base metal. Some holes or nails can be shaped on inserts to catch on the base metal. Second step is conventional heating the die casting molds up to a critical temperature in order to avoid distortions and thermal shocks in mold and inserts [3]. Next step is placing the inserts to exact positions on the molds. It is very important that they must not move by closing the molds or pressure of the liquid base metal. Forth step consist of injection of non-ferrous base metal into the molds. Metallurgical parameters play crucial roles on the achievement of the process. The final solidified product is non-ferrous metal part including steel inserts. There is no post-operation except getting rid of casting crust at mold contact. Part is ready for service with good surface finish and perfect dimension.

It is known that iron and zinc forms many intermetallics including Γ (Fe_3Zn_{10}), δ ($FeZn_{10}$) etc. [4] These intermetallics are not preferred due to low shear strength values of them which cause crumbling at the interface.[5] Thus, stainless steel and corrosion-proof materials are chosen for inserts.

2. EXPERIMENTAL METHOD

In order to evaluate produced parts in real service conditions, it should be preferred to choose one of the recent weapon components facing cyclic impact loading. Thus hammer of H&K 33 infantry rifle is dedicated for experiments. Mechanism was simulated in mathematical model that, acceleration, momentum and final speed were calculated. Whatever the material is, it must be capable of surviving 8000 impacts on pin (5mm Radius) having 58 HRC hardness [6]. The last speed of the hammer was found 7.9 m/s which mean 0.97j per impact. Reliable examination of produced parts can be attained by assembling parts into the weapon and firing thousands times at artillery range. Durability of the integrity of the part, especially the possible crack propagation and failure at the region between two inserts (figure1) were the first considerations. Finite element analysis was confirmed (figure 2) that most of the stress concentration occurred at that area where force was applied to move the hammer. Second important observations focused on impact point. Hammer hits a pin having 5mm diameter at

Figure 1: Dedicated rifle component. Arrow shows the impact direction. Blue region is base metal (ZAMAK 7) and gray region represents steel insert

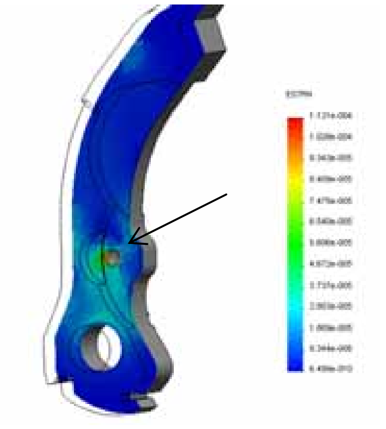

Figure 2: Finite Element Analysis of elastic strain after 4000 cycle. Arrow points the region where highest strain occurs.

that point. Contusion is possible failure that macroscopic examination should applied on operated products. Third and one of the most important facts is interface dissociation caused by elastic and plastic deformations. Steel should not be allowed to deform since it will result as bulging or deforming the base metal surface. Dissociation of interface damages insert-base metal integrity which means undesirable stress concentrations yield failure by fatigue. Because of these facts, as produced parts and operated parts were compared under microscopy in order to examine behavior of the insert – base metal interface. Dewinter Material Plus software was used to compare the size of interfaces quantitatively.

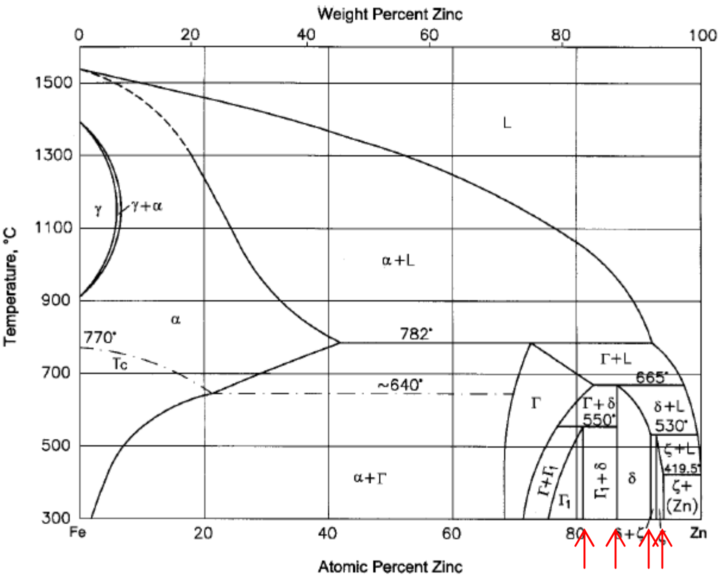

Figure 3: Phase Diagram of Iron and Zinc. Red arrows show intermetallic compositions. [4]

Interface was also investigated for intermetalic formations especially between iron and zinc. There are four different intermetallic and many phases between Fe and Zn (figure3). It was estimated that Molten ZAMAK and steel contact time is about 2-5 seconds. However diffusion of these elements is possible even there is very short time. [4] As it is mentioned above, presence of these intermetallics cause interface dissociation by crumbling due to their low strength values, undue elastic modulus and variable thermal expansion coefficients [5].Using stainless steel (AISI 303) or stainless proof cold work steel (1.2379) could eliminate Fe-Zn interactions by high Chromium content. It is known that there are no phases or stable intermetallics between Cr and Zn at that temperature range [7]. Separation of iron and zinc elements by Chromium oxides could avert these formations. However it must have been verified that XRD technique was performed at interface by Rigaku Dmax ultima++ 2200 PC X-ray diffraction device. 2θ was carried out between 10° - 100° in order to search for all phases.

The main limitation of the die casting processes is porosity due to release of dissolved gases during solidification and entrapped air caused by turbulent molten liquid during injection. Many methods like vacuum systems, air chambers etc. have been applied to overcome this problem but they have not been suitable for every geometry or not successful enough to reach perfect mechanical performance. Recently, porosity of die cast products cannot be eliminated but it is controlled with adjusting some metallurgical parameters [8]. This research do not include any solution for this problem, however, it becomes very threatening since porosities tend to deposit at the insert-base metal interface. Figure 4 proved this fact that porosities (black spots) were collected at the interface. This could cause interface dissociation after cycles of impacts whose detrimental results were mentioned above. In order to get rid of this accumulation, it was predicted to adjust distances of inserts from the gate of the mold where liquid metal enters the cavity might play role on this accumulation. Since molten metal tends to flow from gate toward gaps, higher density of porosity was expected to occur at far regions form the gates. The reason is simple that, liquid metal flows from gates and drives the air with it towards the end of the cavity. Because of this interaction, insert-base metal interfaces close to the gates might not face gas porosity accumulation as much as the ones far from the gates. To test it, interfaces of the both inserts which were located near the gate and far from the gate, and examined by microscopy quantitatively.

Figure 4: Gathering of the porosities close to the interface (100x magnification no etching)

As it was mentioned, the aim is to produce parts working under cyclic high impact loadings. It is worthless if mechanical requirements are not satisfied. Thus, steel inserts and the base metal can operate without any yielding or crack propagation. It can be achieved by using high strength steel as inserts which must have high toughness and hardness too. AISI 303 steel do not have very high yield strength and hardness in cold drawn condition (495 MPa, 23 HRC) when it is compared to 1.2379 cold work tool steel (1370 MPa, 57 HRC). However AISI 303 austenitic stainless steel performs 115j (@ 21°C) at Izod impact test while 1.2379 has 77j in tempered condition. (@21°C) [9]. This is advantage of AISI 303 since it yields high fatigue performance. AISI 1.2379 has excellent strength, hardness and wear performances when all heat treatments are applied sensitively. It was taken as annealed condition with 36HRC, heated up to 1030°C and held about 35 minutes to ready forced air quenching. Hardness was elevated to 62 HRC and steel was carried to two tempering process at 480°C about 2 hours. Final hardness was estimated as 56-58 HRC. Both parts (AISI 303 and 1.2379) were brought to artillery range to try on weapon. Operated parts were carried to macro and micro investigation to check for any crack, smash or interface failures.

3. RESULTS AND DISCUSSION

3.1. Finite Element Analysis: Results of Simulations shown in figure5. Solidworks 2010 Simulation software was used for analsis. Yielding occurred on impact point of AISI 303 insert as it is seen in figure 5a. No plastic deformation was seen in AISI 1.2379 inserts. Stress distribution which is seen at figure 5a after the first impact,

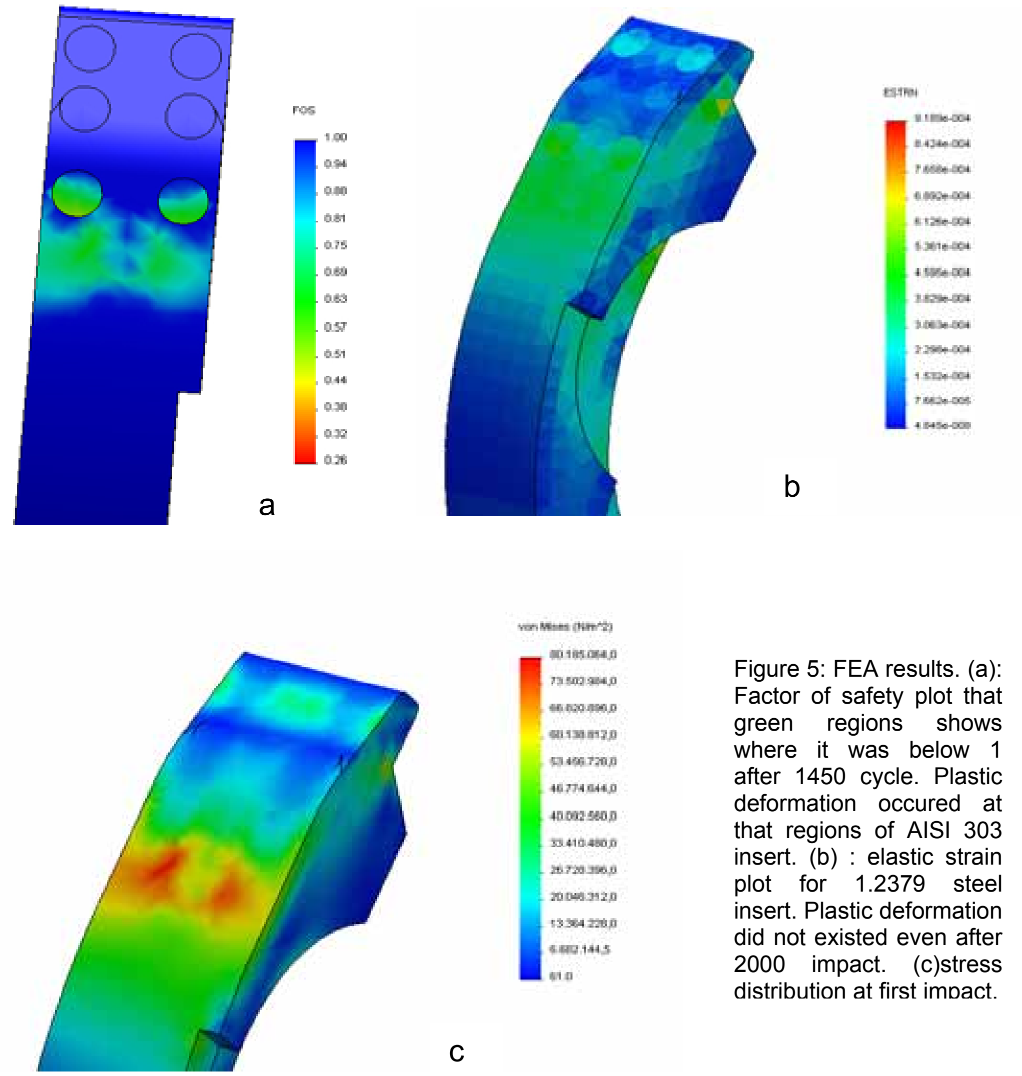

Figure 5: FEA results. (a): Factor of safety plot that green regions shows where it was below 1 after 1450 cycle. Plastic deformation occured at that regions of AISI 303 insert. (b) : elastic strain plot for 1.2379 steel insert. Plastic deformation did not existed even after 2000 impact. (c)stress distribution at first impact.

supported plastic deformation at figure 5a. Area around the region where impact occurs had maximum stress distribution. The plastic strain also affected the interfaces where base metal and insert meet (figure 5c). The plastic strain at the base metal (on two teeth) in the figure 5a, also proved it.

3.2. Macro-Investigation: Formed parts were carried to artillery range to try and operate on weapon. 400 bullets were fired with parts including AISI 303 steel inserts. Macro-photographs are shown in figure 6b. Contusion is easily seen at impact point. There are also some wear traces on it. This result causes elimination of AISI 303 steel as insert material candidate. Hardness of the insert is major requirement to overcome cycles of impacts. At the neck of the whole body where the force was applied, no crack or yielding was found. This means ZAMAK 7 alloy performed satisfactory durability under cyclic bending loading. Parts with 1.2379 steel inserts were recently tested on weapon during this paper was being written.

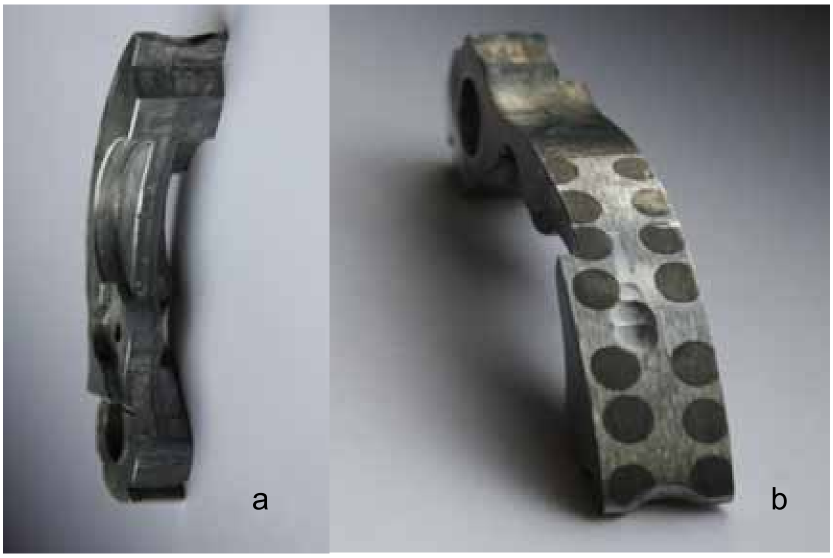

Figure 6: Photos of tried parts with AISI 303 inserts. (a) No deformation at the risky zone where force is applied. (b) Catusion at the impact point.

3.3. XRD Results: X-ray Diffraction technique was applied to the ZAMAK 7 – AISI 303 interface to search any kind of intermetallic formation. Figure 7 presents the output of the XRD as intensity versus 2θ plot. All peaks belongs to Zinc (ZAMAK 7), Iron (steel) and Aluminum (ZAMAK 7). Chromium is possibly hidden behind the

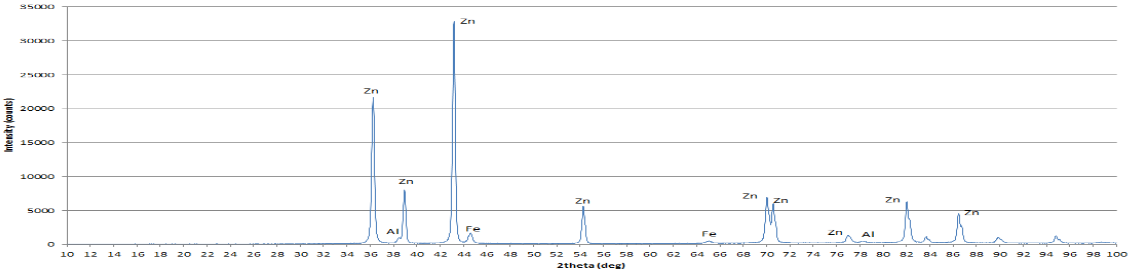

Figure 7: XRD pattern of ZAMAK 7 - 303 steel interface. None of the intermetallics are identified

peaks of iron because of similar peaks. No intermetallic phases were found which supports the idea that Chromium forms oxides at the surface of the steel. This fact avoids elemental diffusion and also do not form any phases or intermetallics with Zn.

3.4. Metallographic Examination of Interface: Interface thickness and regularity of both operated and as-produced parts were compared at figure 8. After Quantitative analysis by Dewinter material plus software, average phase percentage of the interface was estimated about 2.1% at as-produced part while it was 2.4 % at operated part. The increase in the interface area due to delamination was 14% that could be result of plastic deformation due to low yield strength of AISI 303 stainless steel. Therefore this steel may not be a correct insert material. No crack propagation was found but it should not be forgotten that operated parts were fired only 400 times.

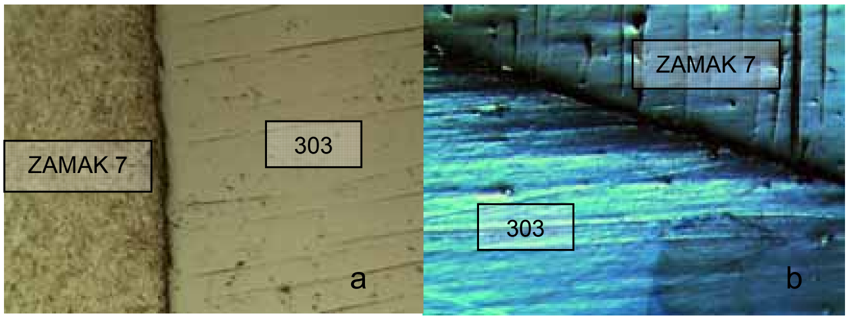

Figure 8: AISI 303 - ZAMAK 7 interfaces of as-produced part (a) and operated part (b) (200x magnification, no etching, low polishing)

Examination of porosities depending on the distance from the gates can be shown in figure 9. Liquid ZAMAK 7 flow carried the air towards the end of the cavity.

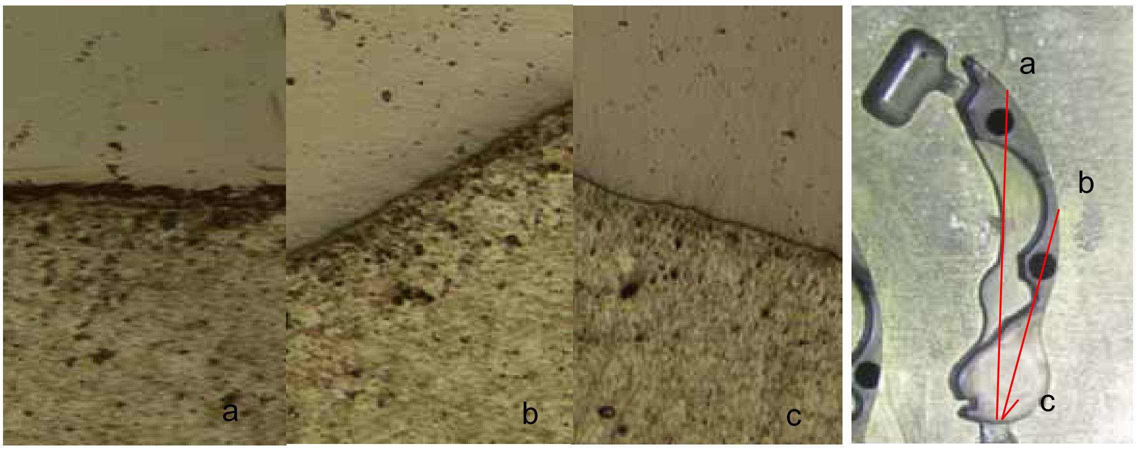

Figure 9: Porosity examination near the interface. Distance of inserts from the gates: 58.6mm (a), 37.8mm(b), 4.9mm(c)

Amount of entrapped air increased continuously with time that when molten metal first reached point “c” on insert, it immediately started to solidify due to relatively much lower temperature of insert surface. Since molten metal has not flowed much yet, entrapped air amount was very low (1.9%). Flow continued and reached point "b". The air in front of the flow was entrapped by turbulence or driven towards a. Some amount of molten metal solidified suddenly at point "b" that driven or entrapped air was boxed in between the molten metal and insert. This explains interface thickening and increased porosity density (2.5%). However molten metal has not completely solidified yet. It continued towards point "a" that the pressure of compressed air between molten metal and mold started to avoid laminar flow of molten metal. This might cause turbulent flows which means very high amounts of entrapped air hit the insert and jammed at the insert and solidifying molten metal(3,9%).

3.5. Other Findings: Sharp corners of the inserts cracked and broke due to the high pressure metal injection. These small broken particles may not be problem itself for the safety of the part but they can be used as surface for gases to stick and grow. Figure 10 shows exact example of this formation. Large porosities at the interfaces are very risky since they are possible crack initiation sites.

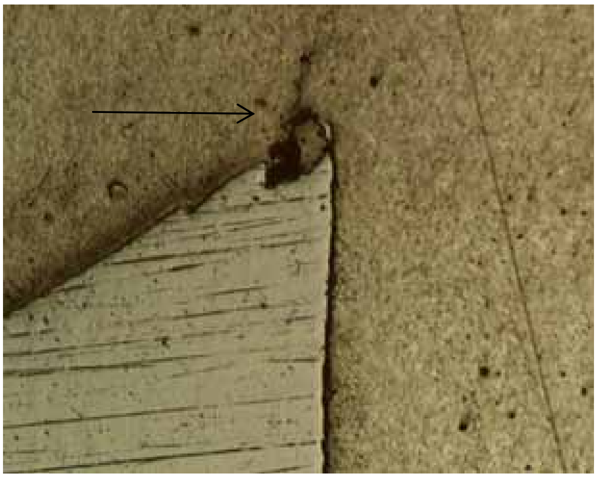

Figure 10: Porosity formation at the broken sharp corners. Crack can be seen above the porosity

The sharp corners can also be threatening during the loadings. They are crack concentration sites that even small loads may trigger crack formation. This fact is fatal since the part faces fatigue failure risk. Stress concentration can reduce fatigue life exponentially. In figure 11, a sharp corner and initiated crack can be seen. Most probably this crack might cause failure if it was applied cyclic impacts.

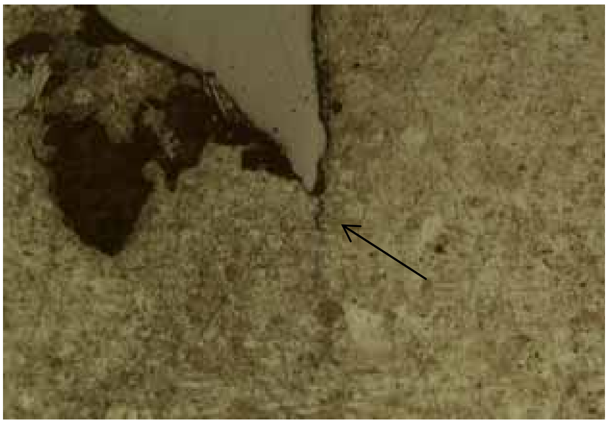

Figure 11: Crack formation at the sharp corner of insert

4. CONCLUSIONS

Production of parts in desired dimensional tolerance without any machining process was achieved. This process eliminated expensive and time consuming 30 or more machining steps. For safety of the part, inserts must be made of material possessing high strength, toughness and surface hardness. AISI 303 was a candidate material due to its high impact toughness and high machinability. However strength and hardness properties did not satisfied the requirements. Thus, study should continue with high performance steel like 1.2379. ZAMAK 7 played its role perfectly that its low elastic modulus and high toughness helped facing repetitive bending moment with high strain rate. I can be used as base metal for further tests. High Chromium content avoided all detrimental intermetallics between iron and zinc. This was proved by XRD analysis that no trace of intermetallics was found. Interface dissociation and delamination risk was initiated after series of impact. Therefore strength and hardness of steel became primary requirement. It was confirmed that Interface porosity density increase with the distance of the insert from the gate. For this process gating design should be made regarding the fact that inserts should be close to the gates as much as possible. Sharp corners of inserts should be avoided to prevent stress concentration in front of the inserts and air entrapment at the insert base metal interface.

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6. REFERENCES

[1] R.S. Montgomery, “Friction and wear at high sliding speeds”, Wear, Vol.36, 1976, P. 275-298

[2] Heckler & Koch, “Process Card of Hammer”, H&K 33 E (A5-103) rifle process manuals.

[3] G.S.A. Shawki ,A.Y. Kandeil., “A review of design parameters and machine performance for improved die casting quality” Journal of Mechanical Working Technology, Vol.16, 1988, P. 315-333

[4] V. Raghavan, “Fe-Zn”, Journal of Phase Equilibria Vol.24, 2003, P. 544-555

[5] K. Mita, T. Ikeda, M. Maeda, “Phase Diagram Study of Fe-Zn Intermetallics”, Journal of Phase Equilibria, Vol.22, 2001, P. 122-125

[6] Turkish Armed Forces, “Specification of H&K 33 Rifle: A5 103 (H&K 33 E)”

[7] Z. Moser, L. A. Heldt, “The Cr-Zn (chromium-zinc) system”, Journal of Phase Equilibria, Vol.13, 1992, 172-176,

[8]B. Andresen, “Die Casting Engineering” , Marcel Dekker, New York, 2005, pp 276-287

[9] J. R. Davis, “Concise Metals Engineering Data Book”, ASM International, USA, 1997, pp 106, 109, 120