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Fracture and Fatigue Evaluation of Injection Moulded 316L Stainless Steel Powder Using Wax–Based Binder

Mohd Afian Omar
AMREC, SIRIM Bhd, Lot 34, Jln Hi Tech 2/3, Kulim Hi Tech Park, 09000 Kulim, Kedah, Malaysia

Norazlan Roslani
AMREC, SIRIM Bhd, Lot 34, Jln Hi Tech 2/3, Kulim Hi Tech Park, 09000 Kulim, Kedah, Malaysia

Noorsyakirah Abdullah
AMREC, SIRIM Bhd, Lot 34, Jln Hi Tech 2/3, Kulim Hi Tech Park, 09000 Kulim, Kedah, Malaysia

Nurazilah Mohd Zainon
AMREC, SIRIM Bhd, Lot 34, Jln Hi Tech 2/3, Kulim Hi Tech Park, 09000 Kulim, Kedah, Malaysia

Abstract – Metal Injection Moulding (MIM) is an advanced near net shape forming process for high quality of complex shapes combined with high properties of materials. For economic reasons, it is necessary to have demand for a large quantity of parts. This paper presents the attempt to investigate the fatigue behavior of injection moulded MIM specimen using wax- based binder system. The stainless steel powder with the median particle size of 16 mm and a binder consisting of major fraction of paraffin wax and a minor fraction of polyethylene were mixed at 160 ^{o}C using a sigma-blade mixer for one hour to prepare the feedstock. The injection moulded specimen was injection moulded using 80 ton metal injection moulding machine with the nozzle temperature of 200C. Prior to sintering at 1360C, the specimens were debound using a combination of solvent extraction and thermal pyrolysis method. The specimens were then sintered under vacuum. The fatigue properties of the specimen were analyzed and discussed. Furthermore, the microstructure study of the sintered specimen also been carried out to look for the mechanism of the failure.

Keywords: metal injection moulding, sintering, fatigue, microstructure

1. INTRODUCTION

Metal injection moulding (MIM) process is drawing much attention as a promising technique, which leads to a large-scale production of metalworking with precision and complex in shape. This industry has established a commercial credibility in the production of many components and it is clear that major growth occur for several types of products ranging from automotive to consumer products. Most of the MIM research currently focus on tensile behavior and mechanical properties and not into the details of the fatigue evaluation. It is important to study the behavior of fatigue of MIM components because fatigue will cause structure failure.

Fatigue damage is a phenomenon associated with the degradation of the mechanical properties of a material due to cyclic loading and represents a fundamental aspect of the overall evaluation of the remaining life of machine parts and components in service. Fatigue damage can compromise significantly the safety of operating mechanical structures subjected to stresses of variable amplitude and therefore constitutes an important consideration in the mechanical design of such structures, in order to guarantee their service operation under safe conditions[1].

During the last decades, lots of designers, engineers and researchers investigated and explored to develop prediction models for high cycle fatigue (HCF) life, as since it take enormous time and efforts to construct a stress life (S-N) curve [2]. According to Landgraf [3], the HCF is recognized as highly influenced by microstructural variables such as grain size, the volume fraction of secondary phase and the amount of solute atoms or precipitates. In the other hand, many investigator have examined the fatigue crack initiation and propagation modes where manipulate the failure of component to breakdown [4-6]. From the authors Chen et al. [7], mentioned that the starting point of failure under low cycle fatigue is mostly related to the geometrical discontinuities on the specimen surface and furthermore of creep-fatigue-environment may enhance the cracking problem.

Fatigue testing involves the preparation of carefully polished test specimens (surface flaws are stress concentrators) which are cycled to failure at various values of constant amplitude alternating stress levels. The data are condensed into an alternating Stress, S, verses Number of cycles to failure, N, curve which is generally referred to as a material's S-N curve. As one would expect, the curves clearly show that a low number of cycles are needed to cause fatigue failures at high stress levels while low stress levels can result in sudden, unexpected failures after a large number of cycles. Fatigue failures generally involve three stages:1.) Crack Initiation,2.) Crack Propagation, and 3.) Fast Fracture.

Fatigue failures often occur quite suddenly with catastrophic (disastrous) results and although most insidious for metals, polymers and ceramics (except for glasses) are also susceptible to sudden fatigue failures. Fatigue causes brittle like failures even in normally ductile materials with little gross plastic deformation occurring prior to fracture. The process occurs by the initiation and propagation of cracks and, ordinarily, the fracture surface is close to perpendicular to the direction of maximum tensile stress. Applied stresses may be axial (tension-compression), flexural (bending) or torsional (twisting) in nature.

Most of the research in fatigue behavior is focus on machining product and process. It is still lack information on the fatigue behavior and evaluation of MIM sintered products. The main objective of the present study is to investigate the fatigue behaviour of using MIM process as the manufacturing of the product for commercial purposes. This will provide an excellent basis for discussing the choice of manufacturing process, material to be used and the adaptability of the process and materials to the mass production using MIM.

2 MATERIALS AND METHOD

Test Piece Preparation

In this study, the injection moulded of austenitic type 316L stainless steel was used with the spherical powder morphology.

The preparation of the samples had been discussed elsewhere [8],[10] The 90 %-22 µm 316L stainless steel powder used in the present study was obtained from Sandvik. The powder loading used was 65vol%, while the binder system was varied at 70/30 for palm stearin (PS)/ polyethelene (PE) respectively. The granulated feedstock was then injected into tensile bars using a simple, vertically aligned and pneumatically operated plunger machine, MCP HEK-GMBH. Feedstock was fed into the barrel and then injected through the nozzle in the mold cavity. Test bars were successfully molded at temperature of 220°C at pressure 300 bar.

The parts which had undergone solvent extraction were subjected to a thermal debinding where the organic binder, mainly polypropylene (PP) was completely removed. At this process, the parts were heated to 450ºC with heating rate of 5ºC/min and holding time of 1 hour.

The components were sintered in vacuum furnace with the heating rate at 10°C/min to the sintering temperature 1360°C, and held for 1 hour at this temperature before cooled down by furnace cool. The dimensions, density and weight of the sintered specimens were measured to calculate sintered shrinkage and final density. Tensile properties of the sintered samples were determined using an Instron Series IX Automated Materials Testing System. The yield strength, ultimate strength and elongation were measured at strain rate of 0.1/s according to the Standard MPIF 50.

Fatigue testing

The fatigue specimens were tested in uniaxial test using a Universal Testing Machine Instron 8800 of 250 kN load capacity as shown in Figure 1. The machine is installed with tensile and fatigue software to record the tensile and fatigue data. Specimens undergo a tensile test to determine its properties ie Maximum load, elongation,yield stress and young's modulus.A low number of tests (1 to 3) are conducted at a set of stress amplitudes that span the expected stress range of the material are recorded for each specimen.Run-Outs (specimens which do not fail after 108 cycles) are and rerun at a higher stress level to maximize the data obtained from the limited specimen set.S-N Curves is constructed

Figure 1. Instron 8800 Universal Testing Machine

The test method was run according to ASTM E606 – 04E1 Standard Practice for Strain Controlled Fatigue Testing. Fatigue is the condition whereby a material cracks or fails as a result of repeated (cyclic) stresses applied below the ultimate strength of the material.

3 RESULTS AND DISCUSSION

Physical Properties

Table 1 represents the physical properties for 316L stainless steel. Specimens of dumbbell shape were designed and fabricated carefully in accordance with ASTM E606 via metal injection moulding process.

Table 1: The physical properties for 316L stainless steel

Physical Properties	316L stainless steel
Green density, g/cm3	4.2±0.4
Sintered density, g/cm3	7.8±0.2
Hardness, HV	250±5
Linear shrinkage, %	15±1

In fatigue tests, the specimen image with its dimensions of austenitic Type 316L stainless steel specimen designs which was tested in transverse direction of axial fatigue testing as shown in Figure 2.

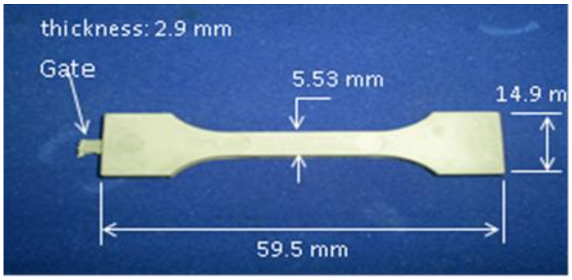

Figure 2: 316L stainless steel specimen designs which was tested in transverse direction of axial fatigue testing

Mechanical Properties

For uniaxial tensile test 3 samples were done and sample results are shown in Table 2. All samples were measured and have an average dimension. The highest maximum stress is at 687.47 MPa and the lowest is at 367.11 MPa. The maximum yield stress achieved is at 635.65 MPa. The stainless steel samples have a mean yield strength of 502.47 MPa. This will be the reference point for the fatigue test as fatigue failure always occurs below the yield point of samples

Table 2 : Mechanical properties of injection moulded 316L stainless steel

	Max Tensile Stress , MPa	Tensile stress at yield (slop threshold at 0.2%, MPa	Modulus, MPa
1	367	332	36414
2	687	635	130569
3	574	539	167434

Fatigue Properties

For the fatigue test the samples were run at 10-90% of the tensile yield strength. Tests were done with a constant amplitude. Three samples were done at each load to ensure repeatability as shown in Table 3

Table 3: Fatigue test the samples were run at 10-90% of the tensile yield strength

Stress (Mpa)	Test 1	Test 2	Test 3
500	711918	692385	702152
400	3311576	4245634	3778605
300	6202179	6911964	6557072
200	10681559	11254041	10967800

Samples were run until failure occurs and the result was plotted to a SN curve. From the SN curve in Fig 5 it shows that at 90% of yield strength or 500 MPa failure occurs at an average of 700000 cycles and at 50% or 300 total cycles to fail is in an average of 6900000 cycles. At 200 MPa the samples did not fail even after 108 cycles.

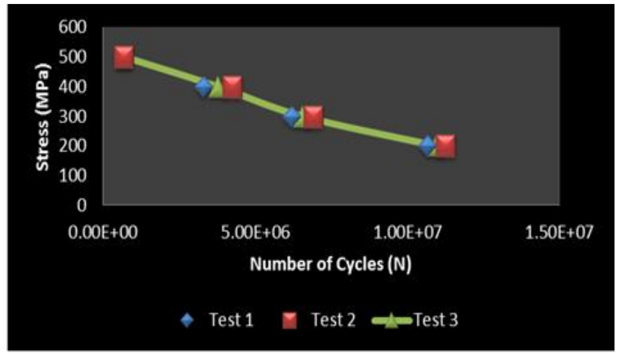

Figure 3: SN curve for injection moulded 316L stainless steel

Fractographic Analysis of Surface

Fracture surfaces were investigated using SEM to investigate the morphological-microstructure relationship which can lead to fatigue faliure. The fracture usually initiates at surface irregularities such as voids and inclusions. Figures 4 shows SEM fractograph for tensile for the stainless steel samples.Samples show normal ruptue due to tensile strain

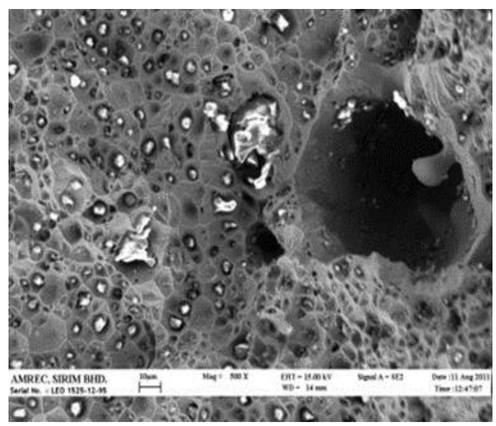

Figure 4: SEM fractograph for tensile for the injection moulded 316L stainless steel samples

Compared to tensile samples, fatigue specimen shows evidence of beachmark due to fatigue failure as shown in Figure 5. Crack initiation and early propagation exhibits the transgranular fracture mode in fracture surface specimens. It shows the fracture strip and which reveals the shear surface morphology. Otherwise, from the figure revealed also the fracture surface has more than one porosity initiation site .Fracture surface of the specimen also shows a propagation zone where mixed fracture path completely intergranular mode in fracture behavior of specimen.

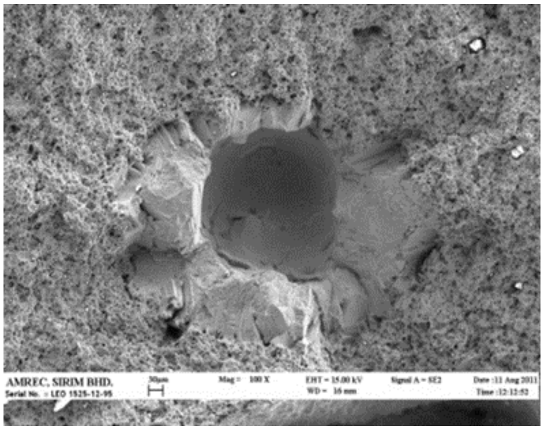

Figure 5: Fatigue specimen shows evidence of 'beachmark' due to fatigue failure

Figure 6 represents the captured picture on fracture surface before failure. Unstable of mode between intergranular fracture and transgranular fracture in this specimen tests was found in final stages (rupture zone). In this stage, fracture surface is look like changed from intergranular to transgranular before reach unstable stage to rupture

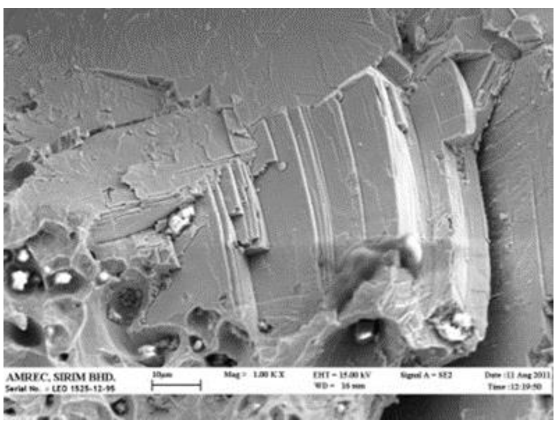

Figure 6: Fracture surface before failure with intergranular fracture

4. CONCLUSION

The average tensile yield strength for metal injection moulded dogbone samples is about 500 MPa. The endurance limit for the specimens are at 200MPa .This is proven because the samples did not fail after 107 cycles. SEM obsevation show that the nucleation crack was transgranular mode, intergranular in crack propagation and last stage exhibits mixed of transgranular and transgranular mode and that porosity is one of the crack initiators.

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