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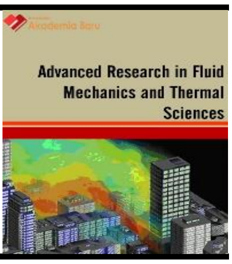

Physical and Mechanical Properties of Fireproof Inconel 718 with Palm Stearin and Stearic Acid Binder

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ABSTRACT

Tensile properties and physical properties of fireproof Inconel 718 have been investigated after under undergoing a high-temperature flame fire test of 1100 ± 80°C with a heat flux of 36 ± 2 kW/m^2 according to the ISO 2685 standard using a methylacetylene-propadiene propane (MAPP) gas burner. The main aim of this study is to understand the physical properties of the different binders and different sintering cycles of the Inconel 718 after a tensile test. The alloys were exposed to a flame temperature for 15 minutes after which they are allowed to cool at ambient temperature before the tensile test. All the Inconel 718 samples of different binders undergo a scanning electron microscope (SEM) micrograph after the tensile test and show different characteristics according to the binders and sintering cycles. The result obtained on the comparison of the different binders and sintering cycles shows that the third sintering cycle is more ductile than the other two cycles with the highest ductility observed on the 68/32-6 stearic acid binder, while the most brittle alloy is the 66/34-5 stearic acid binder in the fourth sintering cycle. From the SEM micrograph, it is clearly observed that an Inconel 718 of the 66/34-12 palm stearin binder has smoother surface grain with huge hollows and low density, therefore the alloy is more porous and penetrable and more prone to break than the other alloys under study. Conclusively, the third sintering cycle proved to be the most effective Inconel 718 for this study due to the excellent properties exhibited by the alloy for both binders.

Keywords:
Inconel 718, high temperature, MAPP gas burner, palm stearin binder, sintering cycle, stearic acid binder

1. Introduction

The super alloy Inconel 718 is a corrosion-resistant nickel chromium-based material that is used for extreme environmental conditions such as high pressure or temperature. The super alloy was introduced in 1965 within the aerospace industry and it has been used extensively ever since due to

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its great tensile strength and impact strength, highly resistant to corrosion and excellent fatigue strength and creeps resistance. These properties made the alloy useful in many high-temperature applications such as in jet engines, gas turbines, and steam generators among others [1-7]. On the other hand, these properties made the alloy very difficult to be machined for powder injection molding [8] and had to be solved by using the metal injection molding process which produces a fine grain size with a uniform distribution of precipitation phases [9, 10]. A stable and a thicker light coat layer created by the oxide layer of an Inconel when heated shield the surface of the alloy from any attack. The Inconel 718 can be fabricated by developing small components that are complex in nature. The alloy materials made up 50% of the weight of aircraft turbojet engines, which are manufactured for various purposes in the aerospace industry. Some of the components made are blades, casings, rings, fasteners, discs, etc. for high pressure and temperature usage in compressors and turbines [11,12].

Many researchers study different attributes of the alloy. The rheological and stability behaviour of the alloy was studied by Abdullah *et al.,* [13] who used powder injection molding in their research. Likewise, the rheological investigation was also carried out in terms of compatibility and homogeneity of the mixture that was measured by capillary rheometer [14-17]. The physical properties of the Inconel with palm stearin and stearic acid binder was reported by Ibrahim *et al.,* [18], where the viscosity and the shear rate of the alloy were studied and found to indicate an increase of shear rate as the viscosity decreases. The conventional binder system used on Inconel 718 was replaced by a greener binder in order to reduce the use of synthetic binders in favor of the natural palm stearin binder and found almost as excellent [19,20].

Inconel 718 undergoes the fire-test for different purposes, but the major reason is to identify the fatigue crack growth behaviour of the material after the fire test [21,22] and the impact strength as in ballistic impact test of fibre metal laminate [23]. It is very important for the alloy to be high temperature resistant to an aircraft application due to its usual locations in the aircraft, for instance, in gas turbines where high thermal efficiency is needed with less fuel consumption and pollution, and in jet engines where an increase in temperature increases the speed and allows higher payload [11,12]. Among the factors that limit the gas turbine designs is the high-temperature load carrying capacity, therefore there is a need of high-temperature resistant super alloys to be used, as heated parts are normally designed to perform close to their temperature and load limit. In addition, the mechanical properties of the alloy degrade for a prolonged time to high-temperature exposure. There will be microstructure changes, grain boundary breakages and oxidations [24]. At the high temperature, the micro-mechanism damages observed are oxidation, creep and cyclic plastic deformation [25].

The mechanical properties of Inconel 718 have been evaluated using different methods. A split Hopkinson pressure bar (SHPB) [26] was used previously, whereby the results show an increase in flow stress of metallic materials as the temperature decreases or the strain rate increases [27-29]. Different methods have been suggested that can be performed successfully for detecting the change in mechanical properties by high-velocity deformation that contains dislocation damping and thermally activated mechanisms [30,31]. Kashaev *et al.,* [32] reported a comparative study of tensile properties and fatigue behaviour of Inconel 718, Inconel 625 and Ti-6A-4V where the result was obtained using micro-tensile and micro-fatigue test techniques on a small volume of the materials.

In this investigation, the Inconel 718 alloy is used to understand the properties of the alloy after a high-temperature fire test using the ISO 2685 standard. The alloy can be used in producing potential aerospace application parts such as wheels, buckets, spacers, and high-temperature bolts and fasteners. The main objective of this study is to assess the physical and mechanical properties of Inconel 718 using greener binders after undergoing the high-temperature fire test. The experimental test rig was designed to suit the burner calibration and fire test of the Inconel 718 alloy. After the fire test, a tensile test was conducted and the microstructure of the alloy was viewed using a microscope. Different binder compositions of Inconel 718 were tested and the one with highest properties enhance the survival of the components under a high-temperature condition. The expected result is an Inconel 718 made using palm stearin and stearic acid binder would have the same or better physical and mechanical properties of an Inconel 718 made using a synthetic binder.

2. Materials and Methods

The specimens under test are the collection of super alloy Inconel 718 that were made with different kind of binders. This super alloy is suitable for casings, fasteners, rings or any compartment inside the fire zones in gas turbines due to its extreme heat resistance and high strength. The binders used are palm stearin and stearic acid of different ratios and sintering cycles. The Inconel 718 with palm stearin and the stearic acid binder has been produced by a metal injection molding (MIM) technology from SIRIM BHD. Five steps were used in developing the Inconel 718, which are tooling, mixing, molding, stripping and sintering [16,33].

Three different sintering cycles were used in making the Inconel 718, which were varied in order to make a comparison between one another. Besides the Palm Stearin Binder Composition, the Inconel 718 was also formulated with the Stearic Acid Binder Composition with Polyethylene and Paraffin Wax (PEPWSA). The Stearic Acid Binder is inexpensive and is a common lubricant for the MIM process. Figure 1 shows the geometry of the Inconel fabricated at SIRIM BHD.

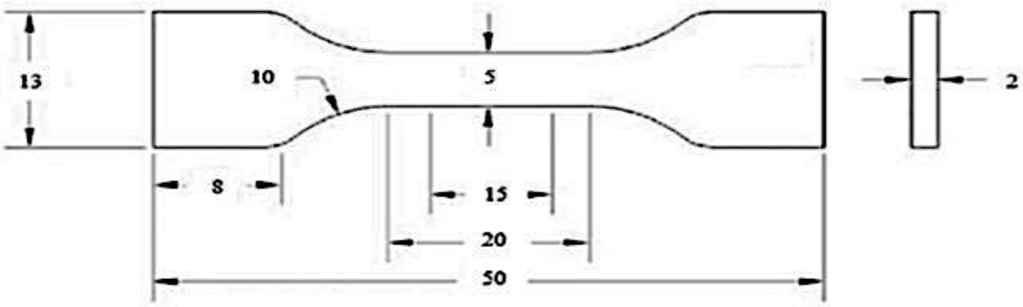


Fig. 1. Geometry of the produced Inconel 718 (mm)

Table 1 shows the compositions of each Inconel 718 fabricated at SIRIM BHD with different binders. After the samples' preparation, the MAPP gas burner, which is based on a stabilized mixture of methylacetylene (propyne) and propadiene, was calibrated by using an R-type thermocouple for temperature calibration and a heat flux meter (SBG01) for heat flux calibration as indicated in Mohammed *et al.,* [34]. The burner was calibrated at an 8-inch distance from the tip of the burner to the measuring devices. The burner was ignited and allowed to settle for at least three minutes and then the temperature calibration was done for three minutes, followed by a heat flux calibration for another three minutes. After the burner calibration, a fire test was conducted on all 14 samples for 15 minutes using the same distance as that of calibration and the results recorded using a data logger. After the fire test, the samples undergo a physical and mechanical test where the microstructures of the samples were studied.

Table 1
Composition of Different Binder Systems and Inconel 718 powder

Sample's number	Sample's Name	Sintering Cycle	Composition	Percentage of volume (%)
1	SA (68/32) 1	1	PE, PW, SA Inconel 718 Powder	32 68
2	SA (68/32) 2	1	PE, PW, SA Inconel 718 Powder	32 68
3	PS (68/32) 1	1	PE, PS Inconel 718 Powder	32 68
4	PS (68/32) 2	1	PE, PS Inconel 718 Powder	32 68
5	SA (70/30) 1	1	PE, PW, SA Inconel 718 Powder	30 70
6	SA (70/30) 2	1	PE, PW, SA Inconel 718 Powder	30 70
7	PEPWSA (70/30) 5	3	PE, PW, SA Inconel 718 Powder	30 70
8	PEPWSA (68/32) 6	3	PE, PW, SA Inconel 718 Powder	32 68
9	PEPWSA (66/34) 11	3	PE, PW, SA Inconel 718 Powder	34 66
10	PEPS (66/32) 12	3	PE, PS Inconel 718 Powder	32 66
11	PEPWSA (70/30) 3	4	PE, PW, SA Inconel 718 Powder	30 70
12	PEPWSA (68/32) 4	4	PE, PW, SA Inconel 718 Powder	32 68
13	PEPS (66/34) 4	4	PE, PS Inconel 718 Powder	34 66
14	PEPWSA (66/34) 5	4	PE, PW, SA Inconel 718 Powder	34 66

3. Results and Discussion

In this section, the fire test result of the MAPP gas burner was presented together with the burner calibration and the physical and mechanical test of the Inconel 718. The MAPP gas burner undergoes three minutes calibration for temperature and heat flux, the result obtained is indicated in Figure 2.

The calibration result obtained was according to the ISO 2685 standard as it is within the range of 1100 ± 80^{0}C for temperature; while that of heat flux is 36 ± 2 kW/m^2 which is below the standard [35] due to the nature of the flame being spread by the MAPP gas burner. All the samples types of Inconel 718 considered in the test can withstand a flame fire of 15 minutes (fireproof) without melting or forming serious crack, except SA 68/32-1 that has a crack at one end of the sample.

Figure 3 shows the average flame temperature test result of all the samples. The result shows that all the samples were burned at the standard temperature of 1100 ± 80^{0}C with a lower heat flux value than the standard [36] as in Abu Talib *et al.,* [37]. This proves that an Inconel 718 made with palm stearin and stearic acid binder of different compositions and different sintering cycles are all fireproof materials.

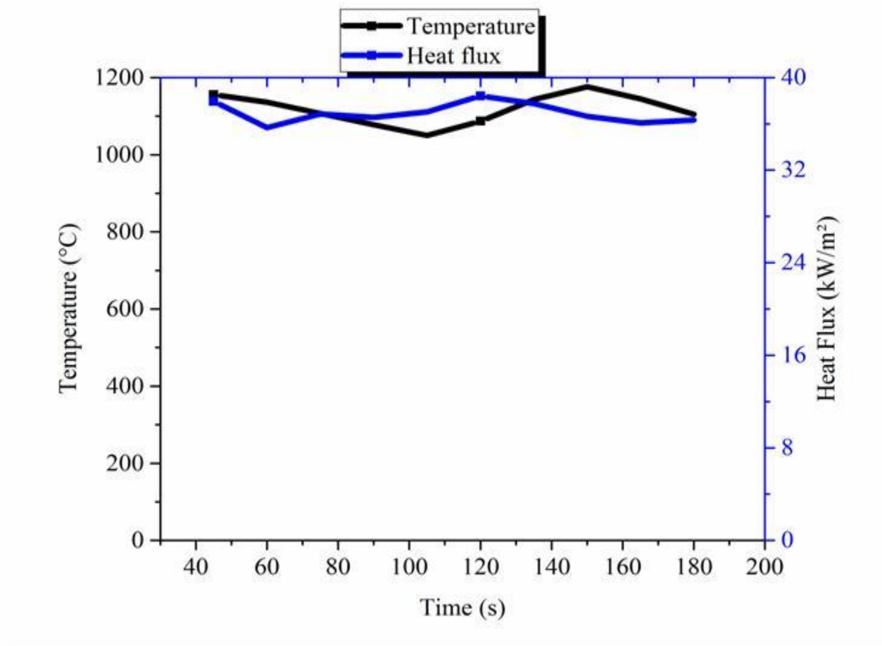


Fig. 2. Burner calibration result

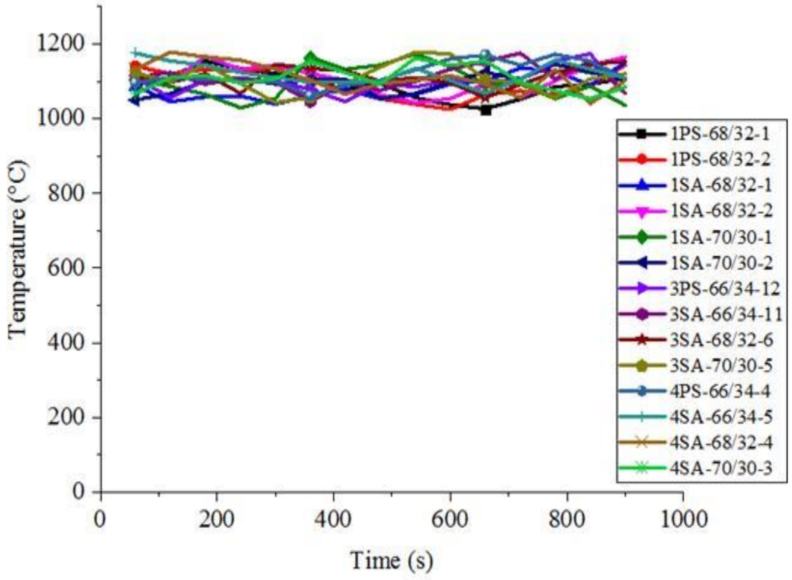


Fig. 3. Inconel 718 fire test result

The physical and mechanical properties of the Inconel 718 after the fire test were shown in Figure 4 where the results of hardness (HV), elongation (%), weight loss (%), shrinkage (%), tensile strength (MPa) and Young modulus (GPa) are presented for the 14 different samples.

The result obtained from the hardness test does not show any major difference in hardness for all of the Inconel 718. The highest hardness observed on the palm stearin binder samples was in the first sintering and the smallest value obtained was on the third sintering. Meanwhile, the highest value obtained from stearic acid was on the fourth sintering and the smallest was on the third sintering. Hardness test is a physical properties test that tests the surface property of the metal and resistance to indentation. It was found that the first sintering samples were more brittle than the other samples, while the third sintering samples were more ductile. The most brittle sample on the stearic acid was the Inconel SA 66/34-5 in the fourth sintering cycle and the least brittle was SA 68/32-6 in the third sintering and was also the most ductile among the samples under study. According to the Vickers hardness scale standard, 350 HV is the limit, therefore most of the values obtained in fourth sintering were very close to the standard value.

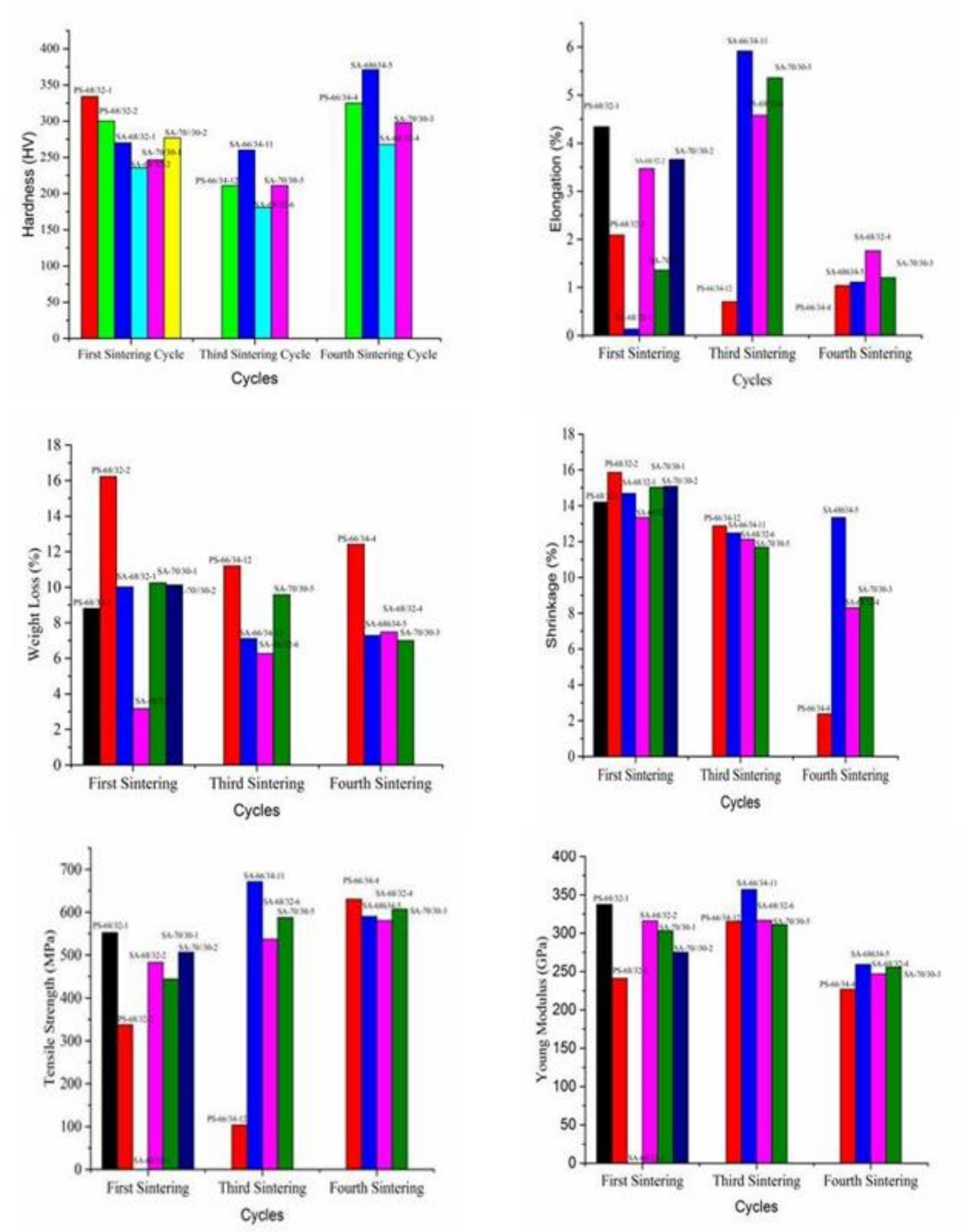


Fig. 4. Physical and mechanical properties of inconel 718 after fire test

The elongation of the samples shows the fourth sintering cycle with least percentage elongation with almost all the values close to 1%, whilst the third sintering cycle recorded the highest value of stearic acid elongation with the highest values close to 6%. This shows that the third sintering cycle can withstand more load than the other cycles before failure; therefore, it has more strain than the other cycles as well as the palm stearin binder sample in the third sintering cycle. The sample with the stearic acid binder from the third sintering cycle shows a staggering percentage of changes in elongation that shows ductile properties, which correlates to their low hardness result of the material. But fourth sintering cycle shows brittle properties that correlating to their high hardness. From Metals [38] for Inconel 718 Technical Data, the typical elongation of Inconel 718 at an elevated temperature is more than 27%. The percentage weight loss of all the sintering cycles was almost the same with palm stearin binder having the highest value in the first sintering cycle and least on the stearic acid binder in the third sintering cycle. Likewise, the percentage shrinkage of the samples was observed in the first sintering cycle on the stearic acid binder and the lowest in the fourth sintering cycle with the palm stearin binder.

In terms of tensile strength, SA 66/34-11 in the third sintering cycle has the highest value compared to all samples and at the same time, PS 66/34-12 of palm stearin in the third sintering cycle had the lowest value, SA 63/32-1 cracked during the process. On average, fourth sintering cycle shows a higher value than the first and third sintering cycles. Therefore, the fourth sintering cycle has highest tensile values and can resist more strength than the other sintering cycles. The typical tensile strength of an Inconel 718 is in the range of 758 MPa but lower if heated to an elevated temperature of greater or equal to 760^{o}C [38]. The values obtained were lower than the values in the Inconel 718 Technical Data resulting due to the higher flame temperature used in the fire test experiment. All of the Inconel 718 showed high values of stiffness. The third sintering cycle and first sintering cycle showed values close to each other, while the fourth sintering cycle shows the lowest overall values. In the case of Young’s modulus, third sintering cycle proved to be the most rigid among the other sintering cycle. From the Inconel 718 Technical Data, the usual value for the Young modulus at above 950^{o}C is 78,000 MPa [38].

The ultimate tensile strength (UTS) of the different binders of all the compositions was evaluated and analyse, the result obtained is shown in Figure 5, for different sintering cycles. From the overall data of Inconel 718 after the fire test, an examination of Inconel 718 with different design parameters (binder composition) is made. The comparison was meant to compare the performance of Inconel 718 that uses different binder compositions (palm stearin binder or stearic acid binder) with the same binder ratios of 66/34, 68/32 and 70/30 using different sintering cycles.

From the ultimate tensile stress (UTS) graph of the values of 68/32 binder ratio, it can be seen that the ultimate tensile strength of the palm stearin binder was around the average of the stearic acid binder’s tensile strength. However, from the same UTS graph, palm stearin binder is shown to be the most desired alloy compared to the stearic acid binder composition. This result shows that Inconel 718 with a palm stearin binder of 68/32 ratio has a good mechanical property and can compete with the synthetic binder. For the binder ratio of 66/34, the palm stearin binder for the third sintering cycle shows a lower value than its stearic acid binder but the opposite is true in the fourth sintering cycle. While for the binder ratio of 70/30, only the stearic acid binder can be considered, after the result reveals that the fourth and third sintering cycles have almost the same values. The lowest ultimate tensile strength value was obtained in the first sintering cycle.

After the tensile test, the microstructures of the samples were viewed by SEM microscope. The micrographs shown in Figure 6-8 are of 1000 magnification. The effect of different binder compositions can be visually seen from the microscopic view after the fire test.

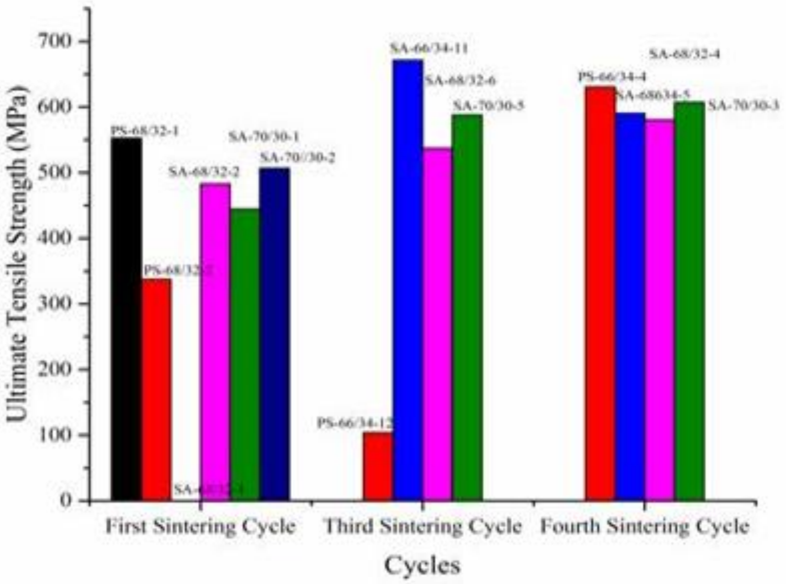
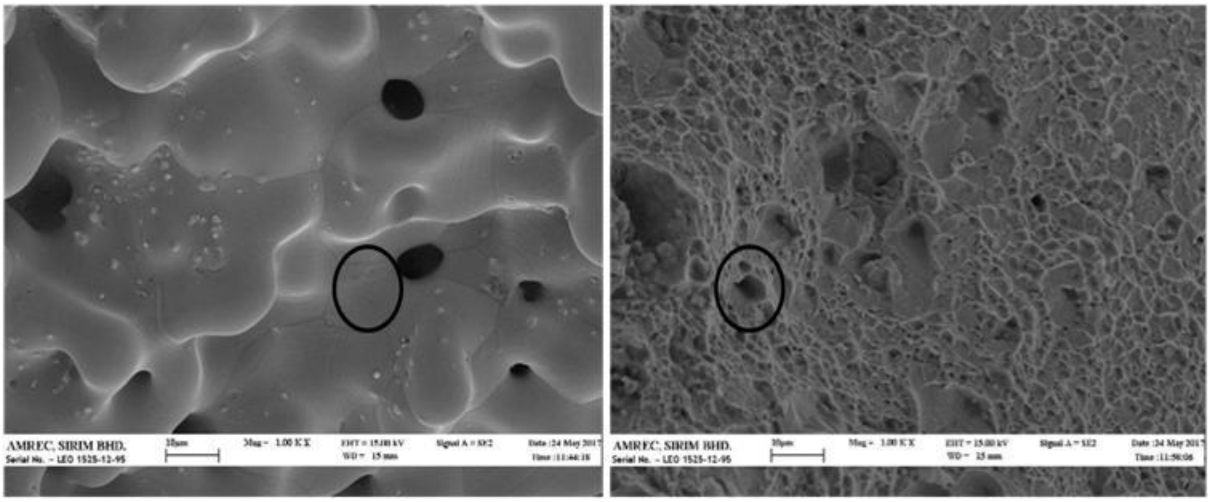


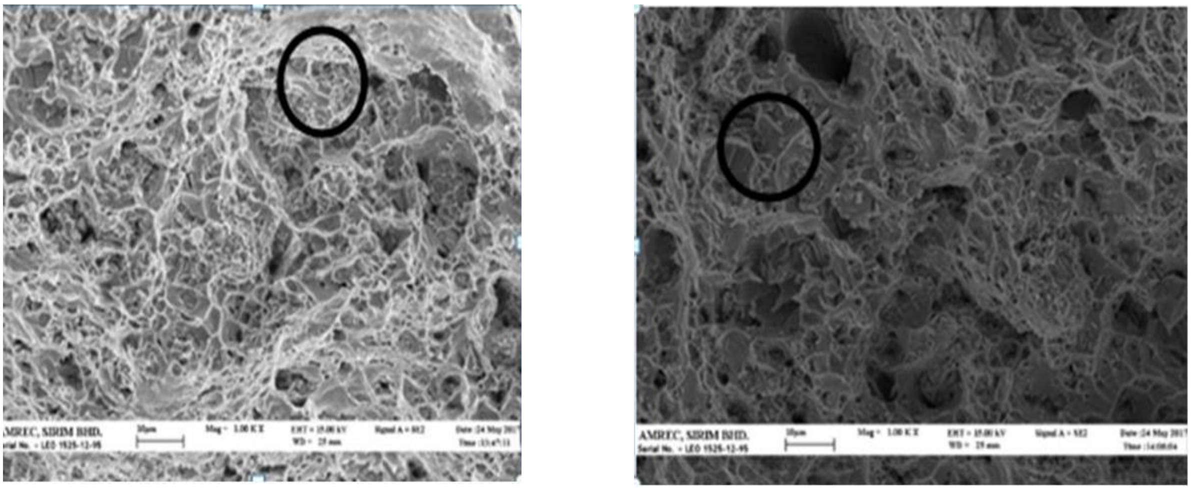
Fig. 5. Ultimate tensile strength of the samples using different binders



(a) Palm Stearin (b) Stearic Acid

Fig. 6. Microstructure view of 66/34 binder of Third Sintering Cycle

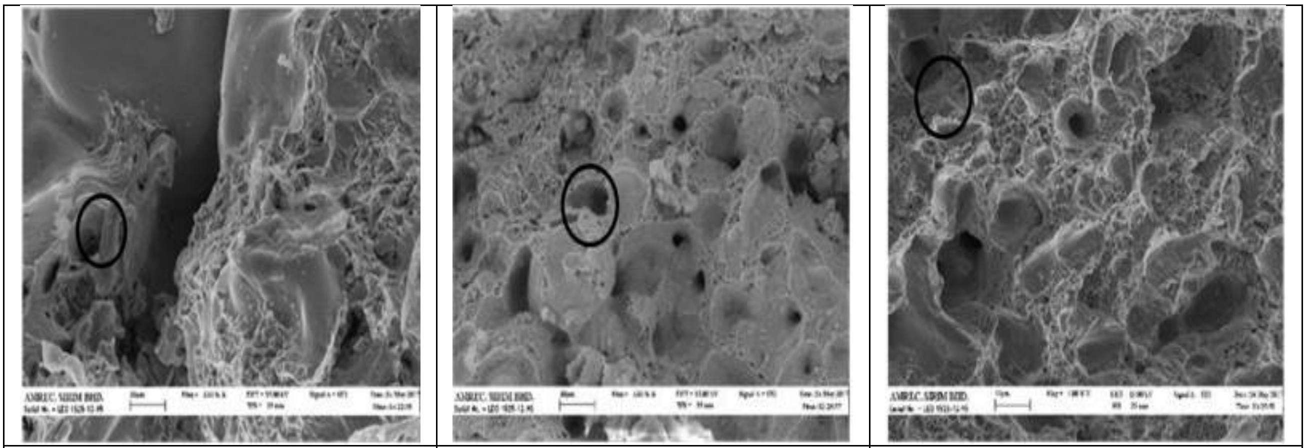
From the structure of the two different binders, palm stearin can be seen to be smoother and subtler than stearic acid, with huge hollow parts in the specimen that make it more prone to breakage and penetrable as compared to the stearic acid composition; with the more subtle surface area. This made its tensile strength very low when compared to the other samples. The result is in agreement with the result obtained by Ibrahim *et al.,* [19]. The microstructure of the 68/32 palm stearin binder and stearic acid binder of the first sintering cycle were also captured after the tensile test.



(a) Palm Stearin (b) Stearic Acid

Fig. 7. Microstructure view of 68/32 binder of First Sintering Cycle

The results of the two binders showed not much difference between the binders in first sintering cycle, with a much bigger hollow area on the stearic acid sample. The surface areas of both samples have almost the same roughness; this made the samples have almost higher values of UTS and Young's modulus, which is also, reported by Ibrahim *et al.,* [19]. The microstructure views of the 70/30 stearic acid binder of the first, third and fourth sintering cycles were also taken after the tensile test.



(a) First Sintering Cycle (b) Third Sintering Cycle (c) Fourth Sintering Cycle

Fig. 8. Microstructure view of 70/30 binder of Stearic Acid

Based on the microscopic images, the Inconel 718 from the third sintering cycle shows much more but small hollow areas than the other two. The third sintering cycle also has a higher consistency of holes and solid surface, with smoother and subtler exterior surface than the other samples, which translates to a higher Young modulus and plastic deformation of the sample. Likewise, the fourth sintering cycle with smaller hollow areas and rough surface of the sample prevents it from plastic deformation, making it has higher tensile strength. This type of result was also observed in Ibrahim *et al.,* [19].

4. Conclusions

In the current investigation, 14 samples of Inconel 718 of different greener binders (palm stearin and stearic acid) with three types of sintering cycles were analysed after a standard fire test of a high temperature of up to 1100 ± 80^{o}C. Based on their physical and mechanical properties of a fireproof alloy, the microstructure results after a tensile test were discussed accordingly. The results showed that both types of alloys, based on their physical and mechanical properties, can be used in jet engines as they can withstand the required strength in the high-temperature application except for the 66/34 palm stearin binder which has a low tensile strength and is prone to breakage and can be more penetrable. Furthermore, as indicated from the test, the third sintering cycle alloy is more ductile than the other alloys, indicating that the Inconel 718 on this cycle have more excellent and suitable properties than the other Inconel 718 alloys used in this study. In terms of the ratio of the binders, the 68/32 palm stearin binder is more desired than the stearic acid binder used due to its ultimate tensile strength. In any case, both types of binders have an advantage other than engine safety, being natural binders that can replace synthetic binders.

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