A Study of the Diffusion Characteristics of Tungsten Bar Stock and Tungsten Produced via Direct Metal Laser Sintering (DMLS)

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A STUDY OF THE DIFFUSION CHARACTERISTICS
OF TUNGSTEN BAR STOCK AND TUNGSTEN PRODUCED
VIA DIRECT METAL LASER SINTERING (DMLS)

by

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ABSTRACT
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Jonathan Bruss B.S.
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Using a vacuum hot extraction method diffusivity and concentration of hydrogen were measured in samples of tungsten bar stock and direct metal laser sintered (DMLS) tungsten. It was found that the tungsten bar stock closely adhered to the model established by Frauenfelder. The DMLS samples approximately follow a downward sloping trend over the 500K-1200K temperature range. The trend is opposite of what is expected suggesting processing has a major effect on diffusion behavior. A CFD model was created using ANSYS Fluent to simulate the diffusion behavior. The model functions by separating out diffusion mechanisms and solving Fick’s law with each mechanism treated as its own species. When the results of the simulation are recombined the diffusion behavior of the original part is retrieved. At the coupon level the simulation proved to be an effective tool at predicting diffusion behavior. This modeling technique is intended to be applied to more complex geometries to appropriately design degassing cycles to reduce cycle on time and improve vacuum stability for DMLS formed part
ACKNOWLEDGMENTS

Jonathan Bruss B.S.

I would like to thank God, my wife, my children, and my manager. I would like to thank my teachers, my faculty, my committee, my advisor. I would like to thank the Graduate School and all the Marquette University administration.
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Introduction

Refractory metals such as Tungsten are of interest to produce via direct metal laser sintering (DMLS) because of their thermodynamic and mechanical properties as well as the complex assemblies that are fabricated from them. The common five refractory metals are Niobium, Molybdenum, Tungsten, Tantalum, and Rhenium. These metals are characterized by melt temperatures above 2000°C and relatively high thermal conductivity. Due to the high melting temperature these materials are commonly manufactured via powder metallurgy. Tungsten was chosen as a material to develop in DMLS for its low coefficient of thermal expansion, excellent thermal conductivity, excellent mechanical properties and radiation blocking properties. The print parameter set for Tungsten has been developed in a previous work and will be used as the recipe for this study.

The use of direct metal laser sintering(DMLS) to produce parts for use in a vacuum space is not extensively tested. This study characterizes the outgas potential of DMLS produced Tungsten experimentally and derives a temperature dependent set of parameters to allow for prediction of the outgas performance of Tungsten for non-simplified geometries. The outgas behavior of DMLS produced Tungsten will be compared to experimentally derived results of non DMLS produced Tungsten. The grain size and distribution will be analyzed for both material conditions to help compare the outgas performance.
The solid-state diffusion of hydrogen will be focused on due to its slow diffusion rate and high solubility. The diffusion of hydrogen is well studied in body centered crystalline
materials such as Tungsten and since it predominantly occurs by progressing along interstitial sites its diffusion can be readily modeled.

**Literature Review**

Direct metal laser sintering (DMLS) produces parts by spreading layers of spheroidized metal powder and then sintering a line by use of a 400W Ytterbium (Yb)-fiber laser; the laser then moves a programmed distance known as the hatch width and proceeds to sinter a new line at a programmed speed. Once all lines within a plane are completed and a solid plane has been formed the hatch pattern is rotated by 67° and the next plane is built on top of the prior. 67° is the rotation angle deemed most effective at crack suppression and is commonly used amongst most industrial printers [1,2,3]. Parts are then often vibrated to remove excess powder and stress relieved in an oven prior to removal via electrical discharge machining (EDM). The DMLS process can serve as a very powerful design tool but the material properties can vary significantly. Macroscopic properties such as thermal conductivity, hardness and diffusivity can vary directionally due to print settings. These properties vary due to the morphology of the material grain.

**Figure 1 - DMLS High Level Process**
There are many solid-state diffusion mechanisms that may present themselves and each has a unique set of circumstances to enable it. Most defect driven diffusion mechanisms require a high activation energy, high temperature, and tend to present very low solubility since they are limited by the number of defects present in the material[4]. There are of course surface trapped layers which can present themselves as rapid diffusants and their solubility will depend on the sample. These trapped layers are thin layers of gas trapped via intermolecular forces that will diffuse into the surrounding volume given a favorable concentration gradient and temperature. There are substitutional mechanisms however these tend to be seen when the diffusant is similar in atomic size to the medium in which it is diffusing [4]. In the case of trapped gases an interstitial mechanism is most common.

Interstitial diffusion of a gas trapped within a solid is a well-studied subject [5,6-16]. Hydrogen due to its small atomic size tends to locate at interstitial sites within a crystalline lattice. It tends to avoid bonding with the substance whose lattice it dwells in and resists bonding with itself resulting in diffusion that is a result of hydrogen atoms jumping from one interstitial vacancy to another. There are multiple subtypes of interstitial mechanisms however in the case of diffusing gas the most common is also the simplest form. A pure interstitial mechanism independent of material defects tends to dominate gases diffused in solids. Defects that happen to be in a material that gas is diffusing from help to form what is termed a collective mechanism. These collective mechanisms will show an accelerated diffusivity.

Solid state diffusion is a temperature and pressure driven process. Rising temperature forces solute hydrogen atoms to vibrate and once their vibrational energy exceeds the
jump energy required they will jump to the next vacant interstitial site. Hydrogen atoms progress along those interstitial sites by a random walk that is guided by the local jump energies present within the lattice [4]. Figure 2 from Mehrer [4] helps to illustrate the random walk in interstitial diffusion.

![Figure 2 – Interstitial Diffusion Mechanism](image)

When the hydrogen reaches the surface the ambient pressure of the surrounding gas determines the rate of hydrogen leaving the solid. For these reasons, most industrial degassing is done at high vacuum and temperature.

This atomic description can be modeled in bulk like fluid diffusion via Fick’s law. The exception to Fickian diffusion comes in the form of temperature dependent diffusivities and the effect of material defects. Tungsten has a body centered cubic lattice structure
(BCC) [14]. This structure limits the interstitial diffusion of hydrogen by forcing grain boundaries to act like trapping mechanism for diffusing gas, while the alternative, Face centered cubic structure (FCC), function as a fast track enabling faster diffusion of interstitially trapped hydrogen[15]. The BCC lattice behavior makes the grain morphology of a given part important when discussing hydrogen degassing. Figure 3 from Mehrer [4] helps to illustrate the interstitial sites within the lattice of a generic BCC and FCC material.

![Figure 3 - Crystal lattice forms](image)

Printed materials can have very different grain morphology depending on the print method and parameters used to produce material [1].

Typically, diffusivity rises as the temperature rises, additional gas saturated within the solid will also be activated and begin to diffuse out of the material as the lattice vibrates.
more. The mechanisms behind this behavior are many and are often difficult to experimentally distinguish from one another. A material may have many internal defects such as dislocations, porosity or anisotropic grain morphology. These defects will all present themselves during outgassing as a deviation from ideal behavior compared to a defect free single crystal sample at the same temperature and ambient pressure. To calculate diffusivity a functionality for temperature dependence must be assumed. It is typical to assume the Arrhenius form. This exponential temperature dependence has two constants that must be derived from the curve fitting of samples run at a variety of temperatures. The leading constant is known as the prefactor while the constant in the exponential is a quotient of the activation energy and Boltzmann constant. Comparing these results for the classically formed material sample and DMLS produced sample along with imagery and measurements of the respective grain morphologies will give insight into the outgassing cycle that a DMLS part may require vs its classical counterpart.

**Materials and Methodology**

**Test Apparatus**

To determine the effective concentration of a gas species in tungsten at a given temperature a vacuum hot extraction method was used. This method exposes a sample to a vacuum environment and heats the sample at a constant temperature while measuring the partial pressure for multiple species of gas in the chamber. By combining the pressure vs time curve measured with the ideal gas law the molar concentration of a species in the chamber can be calculated. This test can also be used to determine the diffusivity
constant and activation energy through a series of curve fits. Table 1 summarizes the equipment used in this study.

<table>
<thead>
<tr>
<th>#</th>
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<tr>
<td>1</td>
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<td>2</td>
<td>Vacuum Chamber</td>
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<td>Roughing and Turbo Pumps</td>
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<td>Ambrell EASYHEAT</td>
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<td>PID Controller</td>
<td>YOKOGAWA TC10</td>
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<td>Thermocouple Reader</td>
<td>Fluke 714 Thermocouple Calibrator</td>
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<td>7</td>
<td>Type K Thermocouple</td>
<td>SCAXL-020</td>
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<td>8</td>
<td>DMLS Printer</td>
<td>EOS M 290</td>
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<td>9</td>
<td>Residual Gas Analyzer (RGA)</td>
<td>Stanford Research Systems Quadripolar RGA</td>
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<tr>
<td>10</td>
<td>Wire EDM</td>
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<tr>
<td>11</td>
<td>Tungsten Powder, 20um</td>
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Figure 4 shows the test chamber used with attached cold cathode gauge, RGA and RF coil.

To reduce the presence of organic compounds that may volatilize from the surface of a sample each sample was solvent cleaned and ultrasonics were applied. Samples were loaded 1 at a time into the vacuum chamber and pumped down to $1 \times 10^{-7}$ torr. To
achieve a stable temperature an RF coil and power supply were employed driven by a
PID controller. The PID parameters were derived from the samples behavior at 1000 C to
minimize overshoot. Prior to data recording each sample was ramped from room
temperature to 200 C over a period of 20 minutes to help boil off any surface trapped gas.
Samples were then heated in roughly 100 C increments to a limit of 1000 C. This
incremented approach was taken as a bulk degas with virgin samples would raise the
partial pressure inside the chamber too high for the RGA to measure.

Analytical Solution

To calculate the diffusion constants of interest an analytical solution provides a means to
convert the partial pressure data to an equation in terms of time, temperature, geometry
factors, and diffusion parameters. Equation 1 is the partial differential Equation for
diffusion in a cylindrical coordinate frame [4]. Symmetry is assumed which removes the
angular dependence. Equation 1-6 highlight a separation of variables solution method in
3 dimensions. Equation 4 is inserted into the original partial differential equation to
attempt to gain a product solution. Equation 7-10 are the eigen functions that result.

\[
\frac{1}{\rho R} \frac{\partial C}{\partial t} = \frac{1}{\rho} \left( \frac{\partial C}{\partial r} + \frac{\rho^2 C}{\rho} \right) \frac{\partial^2 C}{\partial z^2}
\]

Equation 1

\[
\frac{1}{\rho R} \frac{\partial C}{\partial t} = \frac{1}{\rho} \left( \frac{\partial C}{\partial r} + r \frac{\partial^2 C}{\partial r^2} \right) + \frac{\partial^2 C}{\partial z^2}
\]

Equation 2

\[
\frac{1}{\rho R} \frac{\partial C}{\partial t} = - \frac{\partial C}{\partial r} + \frac{\partial^2 C}{\partial r^2} + \frac{\partial^2 C}{\partial z^2}
\]

Equation 3

\[
C(r, z, t) = R(r)Z(z)T(t)
\]

Equation 4

\[
\frac{RZ\partial T}{\partial t} = \frac{1}{\rho} \left( \frac{\partial R}{\partial r} + DZT \frac{\partial^2 R}{\partial r^2} + RT \frac{\partial^2 Z}{\partial z^2} \right)
\]

Equation 5
The boundary conditions set in place are set to agree with our experimental conditions inside a vacuum environment. The initial concentration is assumed to be uniform on the interior of the part and zero at the surface. The homogenous boundary conditions necessitate an eigenvalue solution and an understanding of the test conditions give the intuition on choosing the best form of the solution.

Boundary Conditions:
\[ C(\pm a, z, t) = 0, \]
\[ C(r, \pm l, t) = 0, \]
\[ C(r, z, 0) = C_0 \]

Equation 9 & 10 turn into a sine series and zero order Bessel function of the first kind. If the first term of the series is taken for simplicity of the curve fitting to follow and apply Equation 4 again Equation 11 results.

\[ C(r, z, t) = C_0 \pi \cos \left( \frac{2\pi z}{l} \right) J_0 \left( \frac{\gamma_1 r}{a} \right) e^{-D(\lambda^2 + \mu^2)t} \]  

Equation 11

To allow for a solution that is conducive to relating to the experimental apparatus and that allows for curve fitting the volume average is taken resulting in Equation 12-13.
\[
C(t) = \frac{\int_{0}^{1} \int_{0}^{a} c_0 \pi \sin \left( \frac{\pi z}{a} \right) J_0 \left( \frac{\pi r}{a} \right) e^{-D(\lambda^2 + \mu^2) t} r r dr dz}{\int_{0}^{1} \int_{0}^{a} r r dr dz}
\]
Equation 12

\[
C(t) = \frac{2la^2 c_0}{y_1} J_1(y_1) e^{-D(\lambda^2 + \mu^2) t}
\]
Equation 13

Equation 14 suggests that the concentration decay may decay at some rate apart from a simple exponential with constant coefficients.

\[
C(t) = \frac{2la^2 c_0}{y_1} \sum_{i=1}^{2} C_{til} e^{-D_l(\lambda^2 + \mu^2) t}
\]
Equation 14

Results and Discussion

Tungsten Bar Stock Micrographs

To begin the discussion of the experimental results we begin with the classically formed 99.95% pure tungsten rod. Tungsten bar stock is made by pressing tungsten powder into the rough form. A hydrogen pre-sintering takes place and then a final full sinter process takes place where current is passed through the material until the tungsten is fully sintered. A swaging process is then performed to take the large bar of tungsten into the size(s) required. For a pure sintering process, one would expect a near isotropic grain structure as the material is not worked in a directional manner. Processing can have a dramatic effect on grain morphology as can be seen in the SEM results of the bar stock.

Figure 5 shows the longitudinal grain morphology at two magnifications. The deformed structures can be clearly seen. This deformation is more apparent when compared to the transverse morphology.
Figure 5 shows the longitudinal optical micrographs of tungsten bar stock.

Figure 6 shows the transverse grain. From this perspective the results of the sintering process are obvious. Now having seen both morphologies it becomes clear that during the formation of the bar stock the grain becomes anisotropic. The grain boundaries can have a significant effect on diffusion behavior. Typically, in a BCC lattice material grain boundaries act as diffusion inhibitors.

Figure 6 shows the transverse grain. From this perspective the results of the sintering process are obvious. Now having seen both morphologies it becomes clear that during the formation of the bar stock the grain becomes anisotropic. The grain boundaries can have a significant effect on diffusion behavior. Typically, in a BCC lattice material grain boundaries act as diffusion inhibitors.
Data Analysis

The diffusion behavior of hydrogen in tungsten is a widely studied phenomena and thus some models are available for the functional dependence of diffusivity on temperature. Data by Frauenfelder [17] and Ahlgren [3] are used in this study to present a range of observed activation energies. A necessary part of these studies is the expelling of surface trapped species prior to passing into temperature ranges that significantly activate interstitial mechanisms. Surface trapped gases can confound the results which happened in several of the initial samples of this study.

To derive the material constants this study is aimed at each new temperature activation was curve fit. A 2-term exponential was fit was used, \( C = C_1 e^{C_2 t} + C_3 e^{C_4 t} \). Comparing this fit to Equation 14 constants \( C_1 \) and \( C_3 \) were taken directly from the curve fit data and diffusivity was derived by equating constants \( C_2 \) and \( C_4 \) to the exponents of Equation 14 and solving for diffusivity. Ahlgren [3] uses a similar technique to derive diffusivities. This fit worked well and allowed the sorting of fast diffusion mechanisms from slow mechanisms. The slow diffusing terms will be most relevant to the interstitial behavior modeled in the previous data sets. Gas desorption curves were curve fit for hydrogen across the temperature range. The diffusivity plot in Figure 7 and Figure 8 show two example data sets which represent the fast and slow diffusivities calculated from the 2-term exponential fits. The concentration plots show the estimation of the activated hydrogen at a temperature.
**Figure 7 - Tungsten Sample#7 Extraction Data**

- Diffusivity [m²/s] vs Temperature [K]
- Data points for Fast and Slow extraction processes

**Figure 8 - Tungsten Sample#8 Extraction Data**

- Diffusivity [m²/s] vs Temperature [K]
- Data points for Fast and Slow extraction processes

- Concentration [PPM] vs Temperature [K]
- Data points for Fast and Slow extraction processes
Diffusion mechanisms are activated at each temperature, the resulting released concentrations of gas can be treated as summative for a given temperature as well as all the previous temperatures at which measurements were taken. This same behavior does not apply across temperature measurements of diffusivity. Diffusivities are only additive at a constant temperature such that if multiple diffusion mechanisms are active the total diffusivity of the sample at a temperature is the sum of all the mechanisms. Figure 9 shows the slow diffusing terms plotted against the interstitial results from Frauenfelder [17] and Ahlgren [3].

Ahlgren proposed a correction to the Frauenfelder data suggesting that the activation energy should be 0.25 eV. The collected data falls within the established limits of the unmodified Frauenfelder data, $D = 4.1^{+5.5}_{-2} e^{-39 \pm 0.08 \times 10^{-8}} \frac{T}{S}$. Each of the DMLS samples appears to approach the Frauenfelder limit as the temperature increases. It is observed that the interstitial concentration, Figure 10, appears to be similar for both cases and that the diffusivities differ significantly over the temperature range. Since the sample preparation and geometry was maintained inference can be drawn that the difference is due to material formation and handling. This effect is likely the cause of high levels of air in the storage and printing environment. The printing environment is held at 99% Argon which is a relatively low purity. The storage of powder was a locked cabinet with no cover gas. The grain structure, seen in Figure 13 and Figure 14, bears some semblance to the bar stock, Figure 5 and
Figure 6, however the grains appear to be less discreetly separated. This difference in grain boundaries may also contribute to the higher than expected diffusivities. Additionally, the specific temperature range that this study focuses on, 500-1300K, tends to be rife with defect driven diffusion in classically formed tungsten; this behavior seems to only be exacerbated in the DMLS material. What this data means in practicality is materials must be stored under high purity cover gas at all points and an outgassing cycle at the powder level is advisable.

A future study may be well advised to polish or surface grind all samples and then solvent clean to help eliminate the influence of surface trapped water vapor and oxides, thorough surface cleaning should be done in addition to the surface degassing at 200°C. The measurement test setup should be changed to use an infrared temperature measurement method rather than the contact-based method. This may help reduce error in measurement as it would be less sensitive to sample placement, less sensitive to the quality of contact with the part and would enable temperature measurement above the limit of commercially available thermocouples in the required gauge. It may be advantageous to verify results via a secondary method such as a radiotracer method which is well established to deliver accurate results [4]. It was not used during this study as the equipment and budget were not available. Many samples were spent to tune the PID controller; future studies should include testing at higher temperatures and using physically larger samples to improve PID stability.
The initial concentration of these substances is difficult to reliably predict as it is highly dependent on material processing. A good example is the wire EDM process. When tungsten is cut via wire EDM in oil oxides are less prevalent but in the modern version of wire EDM, which is performed in water, oxidation is prevalent. Figure 10 shows that the DMLS samples lie on top of the baseline samples with respect to the slow diffusing hydrogen suggesting that the print process does not change the initial interstitial hydrogen concentration. Figure 11 shows that DMLS samples do have a higher fast diffusing concentration of hydrogen which is likely due to surface trapped layers as well as heavily oxidized powder as previously discussed. Figure 12 visually reinforces the notion that DMLS materials have higher surface concentrations of trapped gas by showing the
surface color of DMLS produced tungsten immediately after EDM/cleaning (right) and after vacuum hot extraction (left). Surface trapped gas can be highly volatile and have a much higher diffusivity than interstitial trapped species but usually has a lower effective concentration.

**Figure 10 - Slow Diffusing Hydrogen Concentration From Tungsten**
**Figure 11 - Fast Diffusing Hydrogen Concentration From Tungsten**

**Figure 12 - Post Degas DMLS Tungsten (Left); Pre Degas DMLS Tungsten (Right)**
DMLS Tungsten Micrographs

Looking at the grain it possesses some unique feature with respect to the bar stock tungsten. Figure 13 shows the transverse grain at 100x and 500x magnifications looking left to right. The transverse orientation has a similar look to the bar stock but at higher magnification the similarities break down. It appears the continuous melt and re-melt process characteristic of the DMLS process causes more fusion between the grains than the bar stock sintering process.

Figure 14 shows the transverse grain at 100x and 500x magnifications looking left to right. In the longitudinal direction the grain is misshapen and elongated due to the build process. When looking closely it becomes hard to distinguish what is truly a boundary. Referencing Figure 9 the fast-non-Arrhenius behavior of the DMLS samples may be partially accounted for by the indefinite grain boundaries over most of the temperature range. However due to the poor surface quality of the DMLS samples and additional
trapped gas from storage and sintering it is difficult to distinguish between mechanisms with the vacuum hot extraction test method alone.

![Image](image_url)

**Figure 14 - 100X(left) and 500X(right) Longitudinal Optical micrographs of DMLS tungsten samples**

**Simulation**

The process of designing an outgassing cycle for a part starts by finding published data around the diffusion constants and applying them to an analytical model for a semi-infinite wall found in Crank’s text [18]. The maximum wall thickness of the design is determined and used as the basis for the calculation. The equation is then solved for the desired concentration and a constant temperature is chosen based on the materials grain structure. The maximum allowable temperature should be chosen such that there is no grain deformation. I propose that a more accurate method for determining outgassing times for unique and complicated geometry can be achieved by making use of a commercial CFD package such as ANSYS FLUENT.

Data for the material in question must be taken on a sample with geometry conducive to an analytical solution to the governing diffusion partial differential equation(s). In this
study cylindrical geometry was chosen based on the availability of high purity tungsten bar stock. Using a VHE method one can measure the partial pressure curves convert those curves to concentration versus time and then apply 2 term exponential curve fitting.

\[ C = C_1e^{C_2t} + C_3e^{C_4t} \]  
Equation 15

Comparing Equation 15 to Equation 14 the geometric factors present in the non-exponential terms become confounded with the concentration if the subsequent analysis is to be able to match the experimental results. The diffusivity can be extracted from each term successfully. These parameters serve as inputs to the simulation.

The result of these allows FLUENT to solve Fick’s equation(s) in 3 dimensions with multiple species. Tungsten is treated as an incredibly slowly diffusing fluid (<1e-30m^2/s) to simulate it being a solid. The 2 terms of the data fit are input as separate species, a fast and slow diffusing term. The results of the simulation for the fast and slow terms are recombined and the sum will accurately represent the experimental data. Figure 15 and Figure 16 show the results of the modeling technique used to simulate tungsten cylinders.
Figure 15 - Tungsten bar stock 5mm x Ø25mm cylinder at 498K

Figure 16 - Tungsten bar stock 5mm x Ø25mm cylinder at 1178K
This same process can be applied to more complex geometry with one concession. Even with experimentally derived temperature dependent diffusivity the concentration must be assumed for geometry that cannot be solved for analytically. In this case it is most conservative to assume the saturation concentration of gas in a solid and then apply the simulation.

![Graph](image_url)

**Figure 17 - 416L stainless steel 25mm x Ø25mm cylinder at 897K**

Figure 17 helps to illustrate that the model does not diverge as time progresses and that it can be applied to other materials as well. The figure shows H2 evolving from a 25 mm square cylinder of 416 stainless steel and the corresponding Fluent simulation. The error reduces with time to fall under 10%.
Figure 18 applies the diffusivity results from the simplified geometry tested in Figure 17 to a more complex geometry also made from 416 stainless steel. A 2252218 Node polyhedral mesh was used to mesh the domain. Some error can be seen in the outgas results captured in Figure 18; this is primarily due to PID instability and instability due to contact temperature measurement.
Conclusion

The bar stock diffusivities found as a part of this study fall within the $D = 4.1^{+0.8}_{-0.3} \exp\left(\frac{-39^{+0.09}_{-0.1}}{k_B T}\right) \left[\frac{m^2}{s}\right]$ model established by Frauenfelder. The DMLS diffusivities fall significantly above the bar stock results and do not follow an exponential behavior. The total interstitial concentration appears to be in line for both materials. The fast diffusing mechanism is significantly higher in DMLS versus the bar stock samples. The processing effect can be seen in the grain structure as well, as seen in the micrographs. If DMLS parts are to be introduced in a manufactured product the powder should be outgassed and the purity of the cover gas in the print environment should be more on the order of 99.999% pure. This notion presents a unique challenge but perhaps a unique opportunity. If bulk powder can be degassed early on prior to formation and oxidation can be prevented during formation perhaps parts can avoid lengthier degas cycles once the parts are formed and the interstitial diffusion paths are longer. This idea should be pursued as a future line of investigation.

The proposed CFD technique in conjunction with measured diffusivity from coupon testing or the Frauenfelder model allows for a more accurate prediction of outgassing behavior for complex geometry by breaking the solid-state diffusion behavior into multiple diffusive “species”. These species are then recombined in post processing to recover an accurate prediction of the part specific outgassing behavior.
References


18) J. Crank, “Mathematics of Diffusion” (1979)


