METALLURGICAL FACTORS INFLUENCING THE MACHINABILITY OF INCONEL 718

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ABSTRACT

Because of the large volume of Inconel 718 used by the aerospace and power generation industries and the high percentage of metal removed to machine complex component geometries; understanding and improving the machining characteristics of Inconel 718 would result in substantial cost savings. While progress has been made in developing improved tool materials and machining processes, a detailed understanding of the metallurgical factors influencing the machinability of Inconel 718 has not been generated. This paper presents work conducted by United Technologies Research Center and Pratt & Whitney Division establishing the relationship between the metallurgy and machinability of Inconel 718. Factors such as fabrication technique (investment cast, cast + HIP and wrought), hardness, grain size and carbon content were all found to influence machinability. In addition to presenting the relationship between metallurgy and machinability of Inconel 718, suggestions are made in order to improve Inconel 718 machining characteristics and reduce fabrication costs.

Superalloys 718, 625, 706 and Various Derivatives
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Introduction

The characteristic high temperature capability of Ni-base superalloys that makes them ideal for turbine engine applications is also one factor that results in them being very difficult to machine. At the tool-chip interfacial temperatures ($\geq 649^{o}C$) developed during conventional machining, Ni-base superalloys are almost as strong as (or stronger than) the materials used to machine them (Figure 1). In addition, the alloys often contain hard, abrasive particles such as carbides which further contribute to tool wear and breakdown. Finally, Ni-base superalloys readily work harden resulting in strengthening of the workpiece material and a further reduction in machinability.

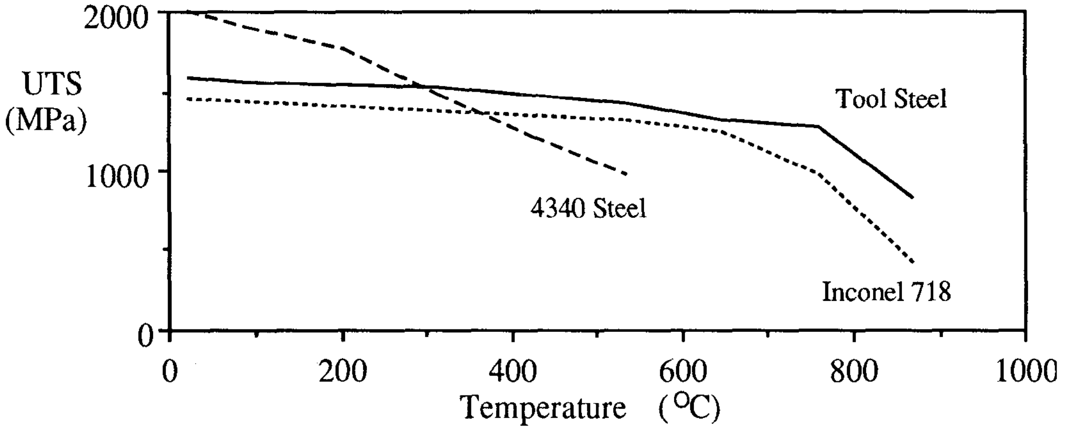

Figure 1. High Temperature Strength of IN718, High Strength Steel and Machine Tool Material.

Despite the sound understanding of Ni-base superalloy metallurgy and general understanding of the relationship between superalloy metallurgy and machining characteristics, research has not focused on altering metallurgical characteristics to improve machinability. Most work conducted has emphasized the development of improved tool materials and geometries or advanced machining techniques (ref 1-7). However, incorporation of these advanced machining techniques often requires a substantial capital investment or imposition of strict process controls. By contrast, metallurgical changes which lower machining costs (like use of sulfur additions to steels) can be readily and cost effectively implemented by primary metal suppliers or metal workers.

Of the superalloys, Inconel 718 has become the workhorse of the aerospace and power generation industries accounting for more than 30 % of all superalloy produced (Ref 8). The sluggish γ'' precipitation kinetics, the relatively high iron content and wide melting range provide Inconel 718 with the unique characteristics of being readily fabricable with all metal forming techniques (investment casting,cold and hot working, die forging,weld assembly,etc) and economic to use. The widespread use of the alloy has resulted in an enormous body of research (3 conferences have focused on it) contributing to a relatively mature understanding of the alloy, its processing and capabilities and limitations. A portion of the research has been aimed at reducing the fabrication cost of components made from the alloy through near net shape forging and investment casting, improved ingot melting and reduction and reduced heat treat time. However, little research has been conducted on improving its machining characteristics.

Because of the widespread use of the Inconel 718, improvement of its machining characteristics could result in significant manufacturing cost reductions.For example, Inconel 718 accounts for approximately 30% to 40% of the weight of current generation large turbofan engines such as the PW4000 and CF6 (ref 9). Assuming a 'buy to fly' ratio of 5, approximately 6000 Kg of Inconel 718 are machined away to produce the finished components. Conventional machining operations such as milling, drilling and turning have an average metal removal rate of about 3.28 cm^3 per minute for Inconel 718 which results in approximately 3625 hours of machining time to produce the final component geometries. Assuming typical machine time labor rates, this represents a cost of up to \$300K for chip making time only (does not include the cost of machine set up, consumable tool usage, coolant usage, machine power usage, etc). This is over 35% of the cost of procuring the original components which is \$814K (assuming an average procurement cost of \$110/Kg). Clearly, machining of Inconel 718 represents a significant portion of the manufacturing cost of a large turbofan engine.

Similar to other fabrication characteristics (weldability, castability, etc), machinability is measured through use of a test where external factors are controlled (tool geometry,coolant, etc) and the behavior of the test material is compared to other materials. United Technologies Corporation uses a free machining (SAE 1020 grade) steel as a reference point for 100% machinability. On this scale, aluminum alloys typically have machinability ratings of over 100%, titanium alloys having machinability ratings of 50% or less and Ni-base superalloys ratings of less than 25%. Wrought Inconel 718 has been rated as 14%. This is consistent with standards established within the machine tool and aerospace industries.

To understand the metallurgical factors influencing the machining characteristics of Inconel 718, the Pratt & Whitney Aircraft Division and Research Center of United Technologies conducted a comprehensive evaluation. Variables studied included metal fabrication process (wrought, investment cast, investment cast + HIP), hardness, grain size and carbon content. Results of the study are presented in this paper.

Details & Results

Drilling was used as the standard machinability test with occasional calibration of machinability ratings through use of milling or turning trials. Table I is a summary of the material and conditions evaluated. The majority of the wrought Inconel 718 evaluated was typical AMS5663 with some PWA1085 (rotor grade forged material) included. The cast material conformed to PWA649 (investment cast) or PWA1469 (investment cast + HIP) specification requirements. To facilitate presentation of the results,the wrought, cast and cast + HIP evaluations will be presented as discrete sections and then compared in the discussion section. The initial section will describe the test equipment and tool wear criteria used for the machinability evaluations.

Table I. Summary of Material and Machining Trials Evaluated.

Material	Drilling	Milling	Turning
Wrought Inconel 718 (ASTM 2)	X		
Wrought Inconel 718 (ASTM 4)	X		X
Wrought Inconel 718 (ASTM 6)	X		
Wrought Inconel 718 (ASTM 10)	X		
Investment Cast Inconel 718	X		
Cast + HIP Inconel 718	X	X	X
Cast + HIP Inconel 718 (Reduced C)	X		

Machinability Testing Equipment. Drilling trials were conducted using a 1.07×10^7 Joules series II, Bridgeport CNC milling machine with M-42 High Speed Steel or C2 micrograin cemented carbide twist drills. Tool failure criteria were local flank wear exceeding .762 mm, average flank wear exceeding .381 mm or catastrophic tool failure. The machinability rating was equal to the machining speed (relative to that of the free machining steel) at which .381 linear meters of hole were drilled when tool failure occurred. Multiple cutting tools were run at each machining parameter and results averaged in order to establish the machinability parameter.

Milling trials were conducted using a 8.05×10^7 Joules, 1650 RPM spindle, number 4 Cincinnati Milling Machine using a 38.1 mm diameter Ingersol CM587-3CHGA, MAX-I-PLEX cutter body and 4 Carboloy 820, C2 micrograin cemented carbide inserts per test.Widths and depth of cut were held constant at 6.35 mm and 3.96 mm respectively (typical for aerospace applications) with machining speeds and feeds varied. Tool failure was defined as an average nose wear of .762 mm or catastrophic failure of one or more inserts. Multiple inserts were tested to failure at each machining condition. The machinability rating was established as the machining feeds and speeds (relative to that of the free machining steel) resulting in 30 minutes of milling for tool failure.

Turning trials were conducted using a 8.05×10^7 Joules Axelson, .91 meter swing manual turret lathe with Kennametal K-313, TPGN-334 cemented carbide inserts. Tool failure was defined as flank wear exceeding .0381 mm, crater wear exceeding .762 mm or depth of cut notch wear exceeding .635 mm. The machinabiltiy rating was established as the machining speed (relative to that of the free machining steel) resulting in 15 minutes of tool life. Multiple inserts were tested to failure at each machining condition.

All machinability trials were conducted at United Technologies Research Center. Figures 2 and 3 show typical exmples of tool wear and machine set up.

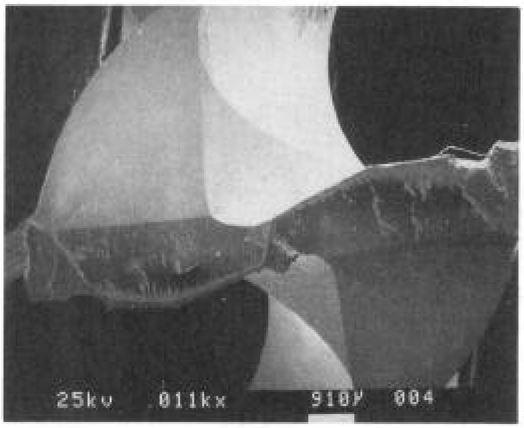

Figure 2. Example of Local Tool Wear

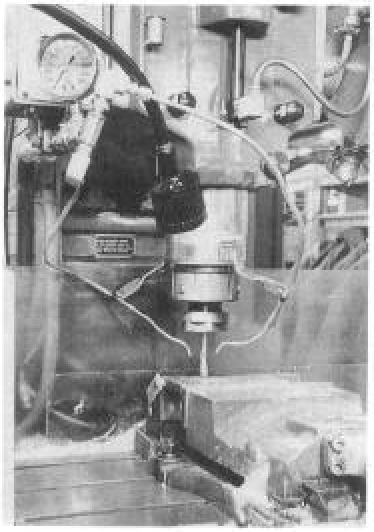

Figure 3. Typical Drill Trial Machine Set Up

Wrought Inconel 718. Three sources of wrought Inconel 718 material were evaluated. The majority of the work was conducted on an AMS 5663 (the composition is listed in Table II) bar forging (10.2 cm by 20.3 cm) cut into 2.5 cm thick slices. Some material was cold rolled and annealed to have a grain size of ASTM 4 to 5 with additional material subjected to a higher temperature anneal to produce a grain size of ASTM 1 to 2. The baseline material had a grain size of ASTM 3. In addition to evaluation in the fully heat treated condition, some of the AMS 5663 material was heat treated to different hardness levels. A second source of AMS 5663 material was a ring forging used for case applications. The third source of wrought IN718 was a PWA1085 disk forging which was selected for evaluation because of the very fine grain size (ASTM 10). Typical microstructures of the materials evaluated are presented in Figures 4 to 6.

Table II : Composition (Wt %) of AMS 5663 Bar Forging used for the Machinability Trials

Cr	Mo	Nb+Ta	Ni	Al	Ti	C	Fe
18.2	3.1	5.24	54.21	.36	.79	.07	17.7

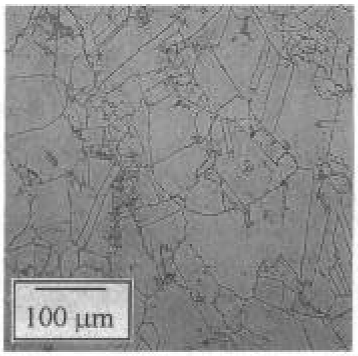

Figure 4
Microstructure of AMS 5663
Bar Forging (ASTM 2-4)

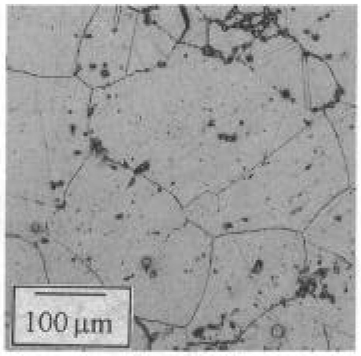

Figure 5
Microstructure of AMS 5663
Bar Forging (ASTM 1-2)

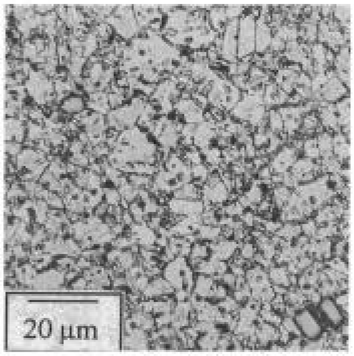

Figure 6
Microstructure of PWA1085
Fine Grain Disk Forging

Table III: Effect of Hardness and Grain Size on the Machinability of Wrought Inconel 718.

Grain Size	Hardness	Machinability Rating
ASTM 1 - 2	44 Rc	15 %
ASTM 2 - 4	32 Rc	18 %
ASTM 2 - 4	38 Rc	17 %
ASTM 2 - 4	42 Rc	16 %
ASTM 4 - 6	45 Rc	19 %
ASTM 8 - 10	45 Rc	20 %
ASTM 2 - 4	42 Rc	14 %*

* Based on turning evaluation.

Drilling trials were conducted on all material with a turning evaluation conducted on fully heat treated/ASTM 3 material. Results of the machining trials are presented in Table III and Figure 7. Note that the machinability of wrought Inconel 718 is reduced slightly by increasing hardness and increasing grain size and that the machinability rating established by the turning trial was slightly lower than that established by drilling. In summary, machinability decreased slightly with increasing hardness and improved with refined grain size.

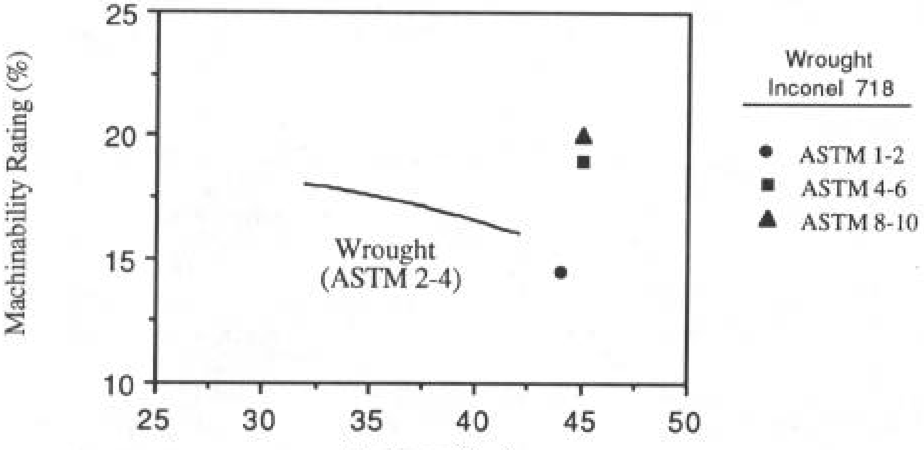

Figure 7: Effect of Hardness and Grain Size on Wrought Inconel 718 Machinability.

Investment Cast Inconel 718. The source of test material used for this evaluation was a PW4000 High Pressure Turbine case casting procured in the as cast condition. The composition of the material is presented in Table IV and the typical microstructure in Figure 8. Similar to the AMS 5663 material, some material was evaluated partially heat treated and also in the fully heat treated condition. The results of the machinability evaluations are listed in Table V. The limited data suggests that machinability decreases with increasing hardness.

Table IV: Composition of Investment Cast Inconel 718 Material used for Machinability Trials.

Heat Code	C	Nb + Ta	Al	Ti	Cr	Mo	Ni	Fe
20676	.036	5.19	.5	.92	18.52	3	Bal	19.21

Table V: Summary of Machinability Drill Trial Results for Investment Cast Inconel 718.

Hardness	Machinability Rating
27.7 Rc	23 %
35.7 Rc	18 %

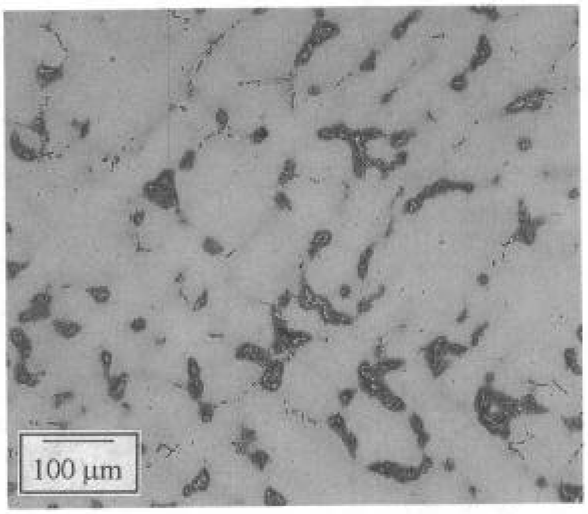

Figure 8: Typical Microstructure of Investment Cast Inconel 718 PW4000 High Pressure Turbine Case.

Table VI: Chemistry (Wt %) of PWA 1469 (Cast + HIP) Machinability Test Material.

Heat Code	C	Nb + Ta	Al	Ti	Cr	Mo	Ni	Fe
20676	.036	5.19	.5	.92	18.52	3	Bal	19.21
VRY113	.05	5.04	.47	.97	19.15	3.1	51.39	Bal
VRY114	.04	4.87	.44	.96	18.8	3.12	51.64	Bal

Table VII: Summary of Cast + HIP Inconel 718 Machinability Trials

Hardness	Machinability Rating
22.5 Rc	20 %
30.7 Rc	20 %
36.3 Rc	18 %
39.6 Rc	13 %
40.8 Rc	12 %
41.0 Rc	11 %*
41.0 Rc	11 %**

* Based on turning evaluation.
** Based on milling evaluation.

Investment Cast + HIP (Hot Isostatically Press) Inconel 718. There were several sources of test material (including the PW4000 HPT case evaluated in the cast condition) and the compositions are listed in Table VI. All material was processed through a 1191°C/103.4 MPa HIP cycle. The microstructures were typical for cast + HIP Inconel 718 and are presented in Figures 9 and 10. As with the other material forms some material was heat treated to various hardnesses. In addition to the drilling trials, a milling trial was also conducted on material at one hardness. The results of the machinability trials are presented in Table VII. The data shows machinability to decrease with increasing hardness.

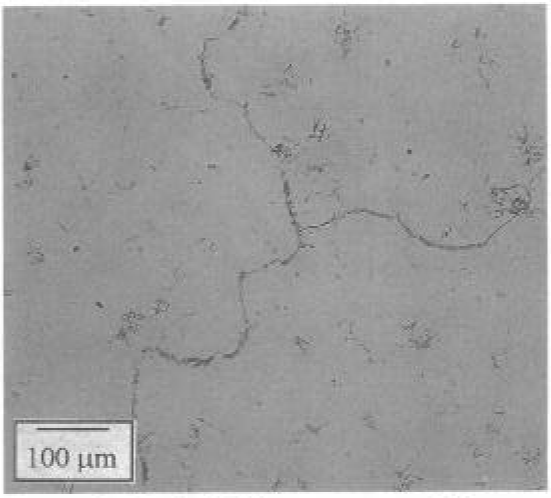

Figure 9: Typical Microstructure of Cast + HIP Inconel 718 PW4000 High Pressure Turbine Case.

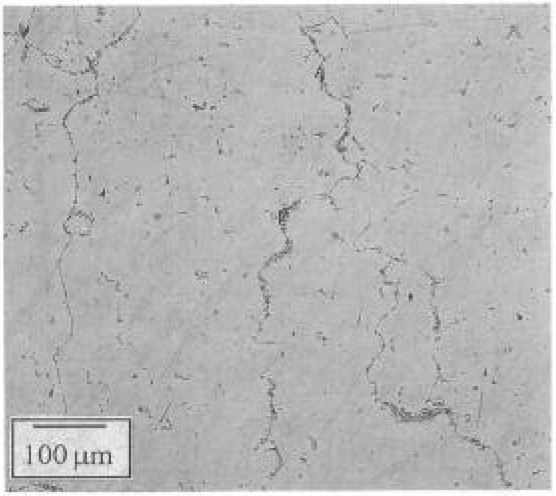

Figure 10: Typical Microstructure of Cast + HIP Inconel 718 Test Panels used for Machinability Trials.

Cast + HIP Inconel 718 With Reduced Carbon Contents. To assess the effect of reduced carbon content on machinability, cast test panels were procured with varying carbon contents. The material compositions are presented in Table VIII and representative microstructures presented in Figures 11 to 13. Quantitative microstructural analysis showed that

Table VIII: Composition (Wt %) of Cast + HIP IN718 Used to Assess the Effect of Carbon on Machinability

Heat Code	C	Nb + Ta	Al	Ti	Cr	Mo	Ni	Fe
D53557	.008	5.16	.52	.91	19.46	3.09	53.25	Bal
D53556	.013	5.06	.52	.88	19.44	3.07	53.35	Bal
D53558	.017	5.04	.51	.89	19.4	3.07	53.14	Bal
D53559	.042	5.05	.5	.9	19.45	3.06	53.09	Bal

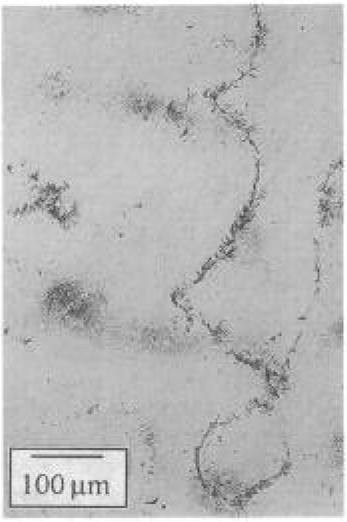

Figure 11: Typical Microstructure of HIP Inconel 718 (.008 Wt % C).

Figure 12: Typical Microstructure of HIP Inconel 718 (.017 Wt % C).

Figure 13: Typical Microstructure of HIP Inconel 718 (.042 Wt % C).

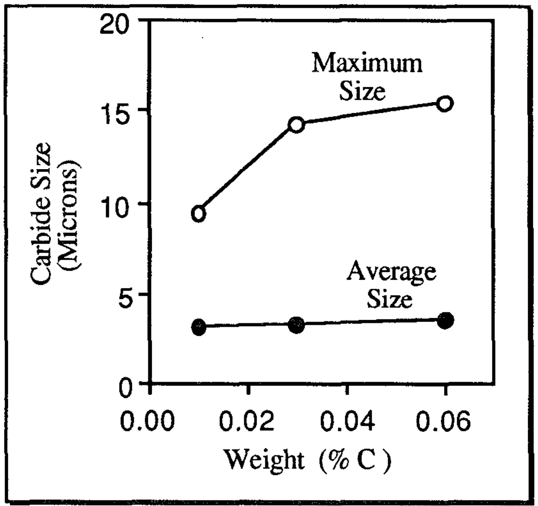

Figure 14: Effect of Carbon Content on Average Carbide Size.

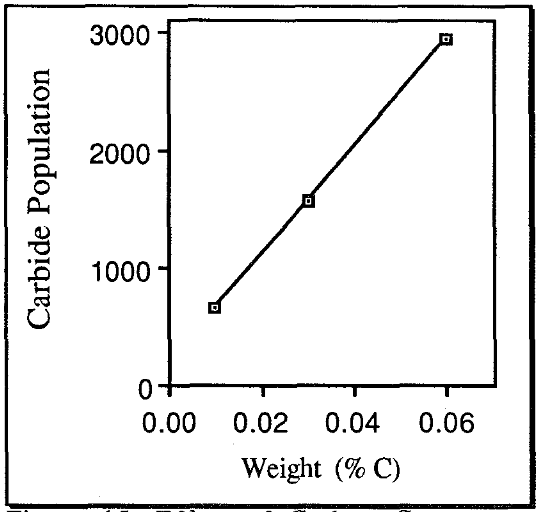

Figure 15: Effect of Carbon Content on Carbide Population per 60 Fields of View.

Table IX: Summary of Machinabiltiy Trials Showing Benefit of Reduced Carbon Content.

Carbon	Hardness	Machinability Rating
.042 Wt %	40.8 Rc	12 %
.017 Wt %	42.0 Rc	14 %
.013 Wt %	43.0 Rc	18 %
.008 Wt %	42.7 Rc	18 %

lowering carbon content did not reduce the average carbide size (Figure 14) but did reduce the maximum size and population (Figure 15). This suggests that average carbide size is established by the solidification rate and not carbon content. In addition, reduced carbon levels resulted in increased hardness due to the increased amount of Nb available for precipitation strengthening (Table IX). The results of the drill trials are presented in Table IX. Despite the increased hardness due to the lower carbon content, reducing the carbon content resulted in a substantial improvement in the machinability of cast + HIP Inconel 718.

Discussion

A summary of all the machinability tests are presented in Figure 16. Several general trends should be noted:

- The machinability of Inconel 718 is relatively independent of product form at hardnesses ≤ 38 Rc.
- At hardnesses > 38 Rc (fully heat treated condition) the machinability of the HIP material begins to decrease more dramatically than the other product forms.
- Machinability improves for grain sizes finer than ASTM 5.
- Reducing carbon content improved the machinabiltiy of the HIP material to levels equivalent to fully heat treated wrought material.

Interpretation of Machinability Results. For the machining speeds and feeds used in conventional machining of Inconel 718, the predominant wear mechanism is abrasion of the tool. Based on this, the machinabiltiy results can be explained as follows. As hardness increases, the strength of the material also increases resulting in an increased tool wear rate and a decrease in machinability. The grain size of the material also plays a role in this. Figure 17 is a schematic showing the relationship between tool feed rate, material grain size and hardness. As the

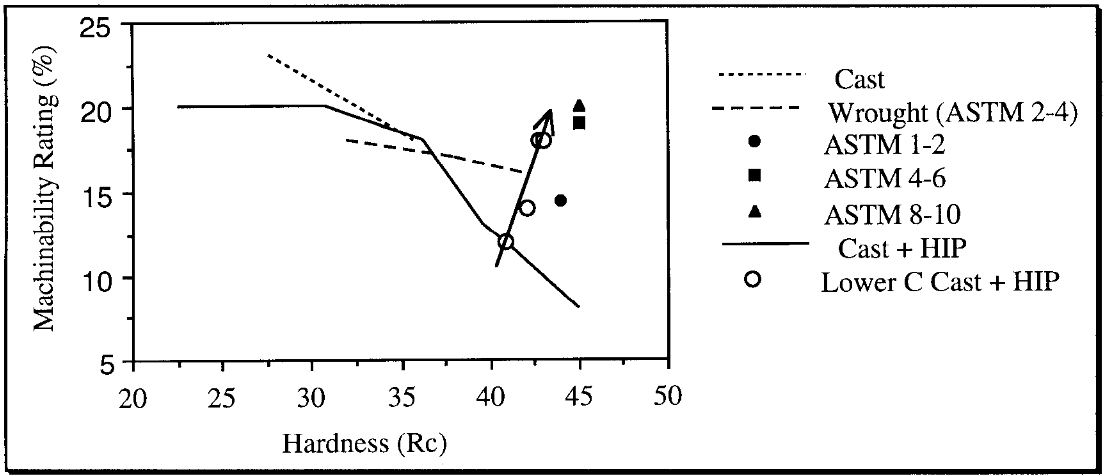

Figure 16: Machinability of Inconel 718 as a Function of Hardness, Product Form, Grain Size and Carbon Content.

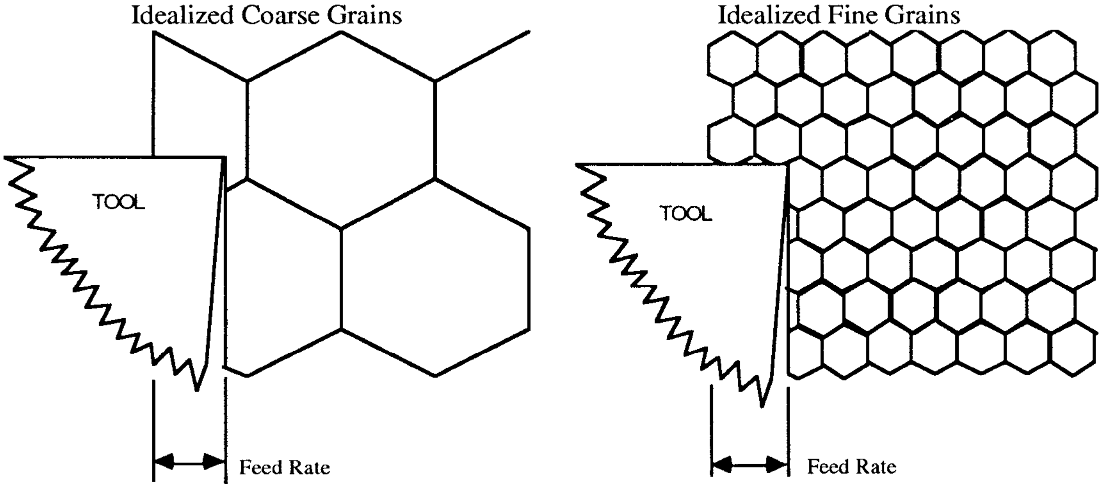

Figure 17: Schematic Illustrating the Relationship Between Tool Feed Rate, Grain Size and Depth of Work Hardened Surface Layer.

tool cuts the material, the region below the machined surface work hardens.The depth of work hardening is usually restricted to approximately one grain diameter deep (the first grain boundary effectively prevents additional work hardening.When the grain size (diameter) is greater than the feed rate of the tool, each successive cut of the tool is cutting material work hardened during the previous cutting pass. This would explain the significant improvement in the machinability of wrought Inconel 718 when the grain size was refined from ASTM 2 to ASTM 5 with only a slight additional benefit for the very fine grain (ASTM 10) material. Typical tool feed rates are .076 to .127 mm per cut which corresponds to a grain size of ASTM 3 to 5. In addition, the very coarse grain HIP Inconel 718 would be expected to show greater decreases in machinability due to the depth and extent of work hardening that occurs (the typical grain diameter is about 20X the typical tool feed rate).

Reduced carbon content results in improved machinability by reducing the amount of hard, abrasive carbides that contribute to tool wear. To validate the beneficial effect of reduced carbon content on machinability and verify that other manufacturing characteristics (castability, weldability, etc) and mechanical properties are not affected, several PW4000 diffuser cases were cast from a heat of low carbon Inconel 718. A summary of the results of this evaluation follows. Pre- and post- HIP non destructive inspection results and weld repair maps were compared for the low and standard carbon cases. There was no significant difference in amount, type or size of weld repairs or NDI indications. A complete set of mechanical property tests were conducted at room and elevated temperatures. In general, the low carbon material showed increased strength and stress rupture capability (Figures 18 to 20) and equivalent fatigue and crack growth behavior (Figures 21 to 22).

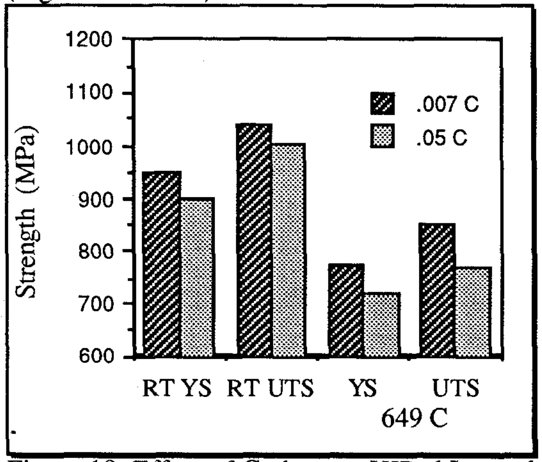

Figure 18: Effect of Carbon on HIPed Inconel 718 RT and 649°C Tensile Properties.

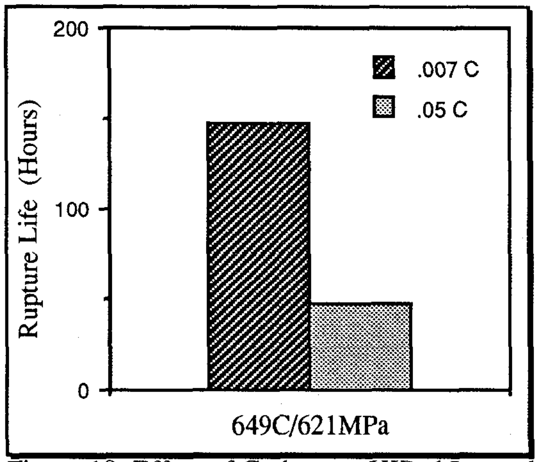

Figure 19: Effect of Carbon on HIPed Inconel 718 649°C Smooth S/R Life.

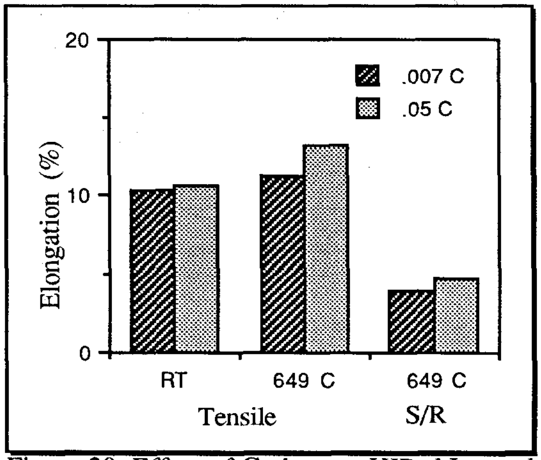

Figure 20: Effect of Carbon on HIPed Inconel 718 Tensile and S/R Ductility.

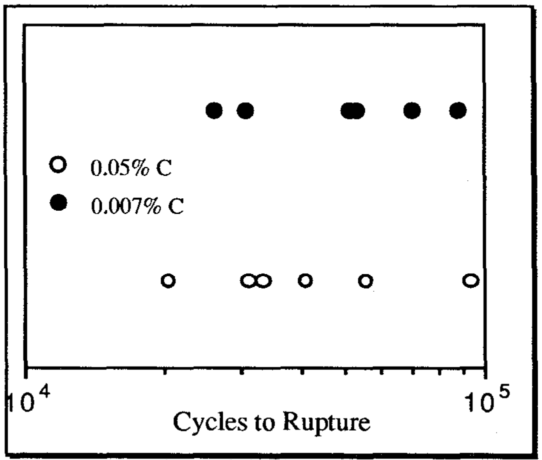

Figure 21: Effect of Carbon on HIPed Inconel 718 593°C Smooth LCF Properties.

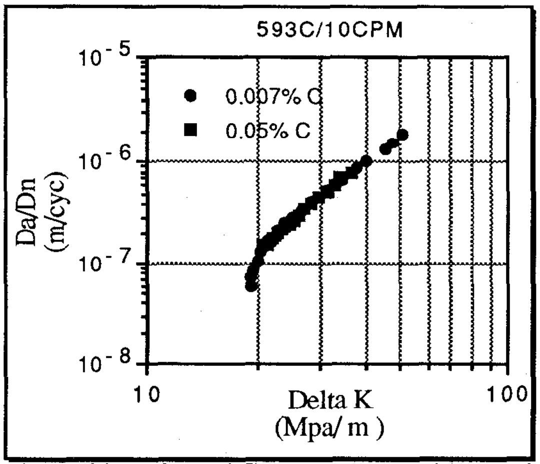

Figure 22: Effect of Carbon on HIPed Inconel 718 593°C Da/Dn Properties.

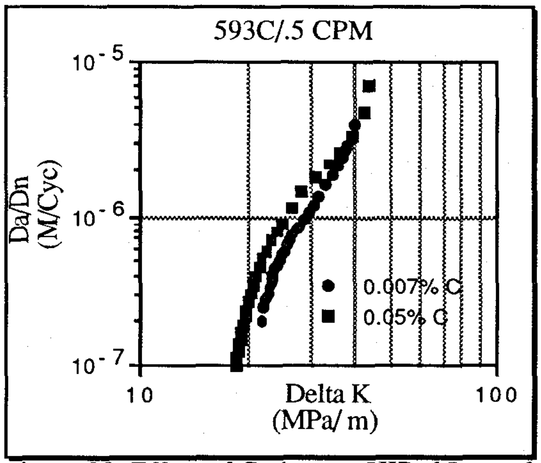

Figure 23: Effect of Carbon on HIPed Inconel 718 593°C Da/Dn Properties.

The standard and low carbon diffuser case microstructures are presented in Figures 23 and 24. Machining trials showed the low carbon diffuser case to exhibit an average machinability of 22 % (compared to 14% for the standard carbon material). In summary, the low carbon case exhibited equivalent mechanical property and manufacturability and significantly improved machinability relative to the standard carbon material. The effect of reduced carbon content on the machinabiltiy of wrought Inconel 718 was not determined.

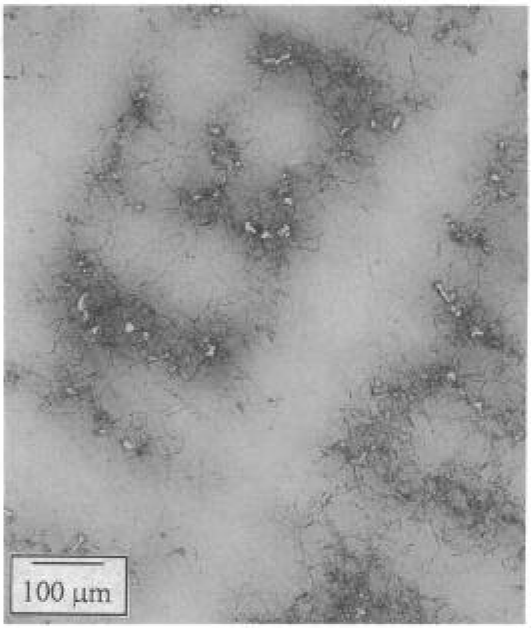

Figure 24: Typical Microstructure of Standard Carbon Cast + HIP Inconel 718 Diffuser Case.

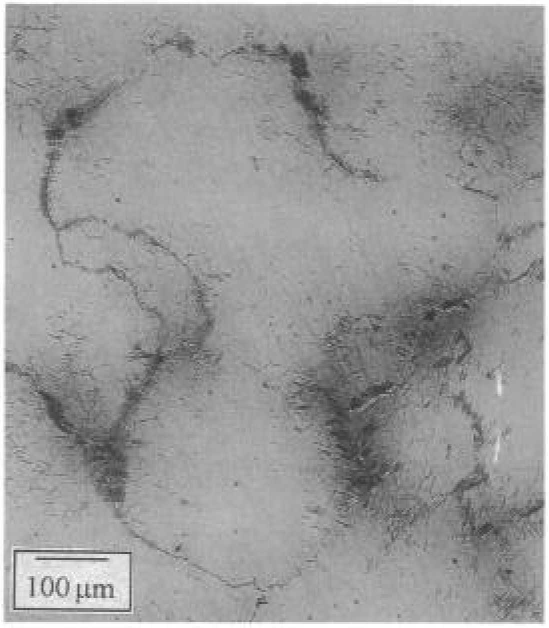

Figure 25: Typical Microstructure of Reduced Carbon Cast + HIP Inconel 718 Diffuser Case.

Process controls to improve the machinability of Inconel 718. The metallurgical factors that can be modified to reduce the cost of Inconel 718 by reducing machining costs are grain size, carbon content and hardness. With respect to grain size, there is some measure of control for wrought material where grain refinement can be attained during the working process. However, machinability improvements due to grain refinement must be weighed against the increased cost and reduced creep/rupture properties of very fine grain processing. Because there is little additional improvement going to a grain size of ASTM 10, the optimum grain size for most applications is probably ASTM 3 to 5. The presence of coarse (> ASTM 2) grains may result in significant reductions in machinabiltiy as they would extensively work harden during the machining process acting as local hard spots, thereby increasing tool wear.

Although machinability generally decreases with increasing hardness, the trend is most prominent for cast + HIP material (machinability is reduced 8% from 20% to 12% as hardness is increased from 22 Rc to 42 Rc). For wrought material, machinability is only reduced 2% (18% to 16%) as the hardness is increased from 32 Rc to 42 Rc. The options available for lowering hardness are altering heat treat parameters or adjusting target composition levels, both of which would affect the mechanical properties of the material. The cost of identifying, altering and qualifying the above changes would not be justified for the small benefit in wrought Inconel 718. With respect to cast + HIP Inconel 718, control or lowering of hardness would be beneficial, however the development work to identify the appropriate factors to adjust and control needs to be conducted and changes qualified.

Reducing carbon content resulted in a significant improvement in the machinability of cast + HIP Inconel 718 (to a level equivalent to as-solutioned,standard carbon machinability) with no detrimental effects on manufacturability or mechanical properties. Although initial material cost may be increased due to a lack of revert material availability, this would reduce as the casting houses (who typically produce their own material including revert) developed a supply of low carbon revert material. It is anticipated that similar behavior (machining,manufacturability and mechanical properties) would be observed for cast Inconel 718, although the experimental work has not been conducted. Reducing carbon content may improve the machinability of wrought Inconel 718, however the detrimental effect of reduced carbon content on mechanical properties has been documented by several investigators (References 10 and 11). Unlike casting houses many forging shops procure revert material on the open market and the inability to use standard carbon revert material would result in a significant material cost premium. For these reasons, incorporation of reduced carbon content would require that the lower carbon material exhibit a substantial improvement in machinabiltiy in order to offset the increased material cost and reduced material capability.

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