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EFFECTS OF HEAT TREATMENT ON THE BALLISTIC IMPACT PROPERTIES OF INCONEL 718 FOR JET ENGINE FAN CONTAINMENT APPLICATIONS

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SUMMARY

The effects of heat treating Inconel 718 on the ballistic impact response and failure mechanisms were studied. Two different annealing conditions and an aged condition were considered. Large differences in the static properties were found between the annealed and the aged material, with the annealed condition having lower strength and hardness and greater elongation than the aged. High strain rate tests show similar results. Correspondingly large differences were found in the velocity required to penetrate material in the two conditions in impact tests involving 12.5 mm diameter, 25.4 mm long cylindrical Ti-6-4 projectiles impacting flat plates at velocities in the range of 150 to 300 m/sec. The annealed material was able to absorb over 25 percent more energy than the aged. This is contrary to results observed for ballistic impact response for higher velocity impacts typically encountered in military applications where it has been shown that there exists a correlation between target hardness and ballistic impact strength. Metallographic examination of impacted plates showed strong indication of failure due to adiabatic shear. In both materials, localized bands of large shear deformation were apparent and microhardness measurements indicated an increase in hardness in these bands compared to the surrounding material. These bands were more localized in the aged material than in the annealed material. In addition the annealed material underwent significantly greater overall deformation before failure. The results indicate that lower elongation and reduced strain hardening behavior lead to a transition from shear to adiabatic shear failure, while high elongation and better strain hardening capabilities reduce the tendency for shear to localize and result in an unstable adiabatic shear failure. This supports empirical containment design methods that relate containment thickness to the static toughness.

INTRODUCTION

International aviation regulatory agencies, such as the FAA in the United States, require that aircraft turbine jet engines safely contain fan, compressor, and turbine blades should they be ejected during operation [1]. To achieve this requirement, all commercial turbine jet engines include some type of engine blade containment system. In some cases this consists of a metal ring that is thick enough and strong enough to prevent penetration of a blade. Steel, aluminum, and titanium systems are currently in use. Other systems are more complex, consisting of relatively light metal or composite rings, a structure such as honeycomb to provide stiffness, and a series of layers of woven aramid fabric to contain the blade. Fabric systems can substantially reduce the weight [2]. However, for high temperature applications, such as around parts of the compressor and the turbine region, or for fans in supersonic applications where conditions are more demanding, it is necessary to use metal containment systems.

While metal systems can be heavy, it is possible to minimize the weight through proper design, material selection and material heat treatment. However, other than by conducting ballistic impact tests, there is currently no reliable method to predict how a material will perform under impact conditions. Sophisticated computer programs are available to simulate impact events, but they rely on accurately modeling the constitutive behavior and deformation and fracture mechanisms that occur. This is still an area of active research and is not yet at a point where accurate predictions of material behavior can be obtained.

There have been a number of investigations aimed at correlating ballistic impact performance with relatively easily measured material properties. A review of some of these studies [3] indicated that hardness measurements of steel armor showed surprisingly good correlation with ballistic penetration properties, and that there was also some correlation between Charpy impact test values and the ballistic limit, the velocity required for a projectile to penetrate a specimen in a particular test configuration. A study by Sangoy et al. [4] concluded that a basic requirement for ballistic armor is that it has high hardness. An interesting conclusion of this study was that for low hardness

steels, where failure occurs as a result of plastic flow in the target, and for high hardness steels, where projectile fracture occurs, there is a strong correlation between the target material hardness and the ballistic limit. However, in the intermediate regime, where the failure is dominated by adiabatic shear, the ballistic limit decreases with hardness.

Impact tests on two titanium alloys [5] found no correlation between the ballistic limit and either fracture toughness or Charpy V-notch toughness. This was supported by a study by Burkins and Love [6] in which the effects of the annealing temperature on the ballistic limit of Ti-6Al-4V were measured. The results of this study showed that changes in annealing temperature affected the tensile strength, yield strength, strain to failure, toughness and Charpy impact strength. However, there was no clear correlation between any of these properties and the ballistic limit. It should be pointed out that the change in static properties due to the annealing was modest.

A number of empirical and analytical models have been developed to predict the ballistic performance of metals based on easily measured material and geometric properties [7]. In many of these models [8 and 9] the perforation energy is proportional to the tensile or yield strength. Corbett and Reid [10] compared a number of empirical models with experimental results and found that the onset of adiabatic shearing is a critical factor in determining the impact resistance of plates. Recht [11] reported that catastrophic shear occurs when local temperature gradients offset the strengthening effects of strain hardening and the slope of the true stress-strain function becomes zero. Under impact conditions involving high strain rates, high strength alloys exhibit unusual behavior in that the rate of work softening arising from the heat generated in plastic flow is greater than the rate of work hardening so that a catastrophic shear develops on a narrow shear plane [12].

Jones et al. [13] used a structural method of analysis formulated using thin plate theory and a rigid-perfectly plastic yield model to analyze the response of circular plates struck by flat faced cylindrical projectiles. Their model accurately predicted the inelastic structural response of plates for relatively heavy projectiles, but they concluded that the model retained insufficient local detail for failure analysis. A similar analysis was performed by Liu and Stronge [14], but their model included the influence of both shear and radial tensile strain on localized failure of the plate. They found that the inclusion of the effects of radial tensile strain yielded more accurate results than those obtained with a pure shear failure criterion and for thin plates gave reasonable agreement with experimental results of the ballistic limit. The effects of temperature were not included in the model. Li and Jones [15] showed that for thick beams, circular plates, and cylindrical shells subjected to impulsive pressure loading shear ruptures and adiabatic shear failures appear with increasing load and intensity and that there may exist a transition between these two failure mechanisms that require different material and failure models in analysis and simulation. This analysis produced the critical conditions necessary for the onset of adiabatic shear failures under these loading conditions, but due to the nature of these conditions, this analysis cannot be applied to the problem being addressed in this study.

Bai and Johnson [16] formulated an analytical model to predict energy absorbed during plugging of a plate by a flat-faced cylinder. This model assumes that only shear strains are present. It incorporates a temperature dependent constitutive relationship and a critical shear strain at which thermoplastic shear instability occurs. The critical shear strain is a function of the specific heat of the material, its strain hardening index, and its thermal softening behavior. The model predicts that increases in both the strain hardening index and the critical shear strain increase the amount of energy absorbed in plugging with the critical shear strain being the most influential. The model also predicts that as the thickness of the plate increases, the energy absorbed per unit thickness begins to level off.

Because of its importance in military applications, much of the ballistic impact work in the literature is relevant to ordnance impact speeds in the vicinity of 1000 m/sec or higher, and typically involve relatively thick targets. There appears to be no static property that correlates well with ballistic impact strength, with the possible exception of hardness. Failure modes are highly dependent on the geometry of the target and the projectile and the physical constraints of the target. Thin metal plates which are allowed to undergo large structural deformations are more likely to fail under tension than thick plates which are more likely to fail under shear in a plugging mode [17]. To evaluate the impact properties of a material for a certain application, it is necessary to conduct experiments under conditions that simulate the use conditions. At impact, velocities that occur in fan containment applications, which are typically less than 500 m/sec and involve targets that are usually thin relative to the projectile, the failure mechanisms are likely to be different from those occurring in high velocity impacts, and the relationship between static material properties and ballistic impact properties could also be different. Empirically based procedures used for containment design currently rate materials according to an approximation of the area under the static stress-strain curve [18]. However, this is just a rule of thumb with a limited range of applicability and the mechanisms behind

this relationship are not well understood. Since it is unclear what static properties, if any, are correlated with the ballistic limit, and since a good understanding of the failure process is needed to model ballistic failure in containment systems, this study was undertaken. Herein, the failure mechanisms and the relationships between static and ballistic impact properties in Inconel 718, at impact velocities pertinent to jet engine blade containment applications, were investigated.

MATERIALS

Three lots of rolled plate material were used in this investigation. Each lot had a unique thickness (1.0, 1.8, 2.0 mm), so that thickness effects could be studied. The material was purchased to meet AMS Specification 5596 and the composition of each lot, as given by the manufacturer, is shown in Table 1. No major compositional differences were observed among the lots. Inconel 718 has a density of 8.19 gm/cm^3 (0.297 lb/in.^3) a thermal conductivity of $11.4 \text{ W/(m}\cdot^\circ\text{C)}$ ($79 \text{ BTU}\cdot\text{in./ft}^2\cdot\text{hr}\cdot^\circ\text{F}$) and a specific heat, C_p , of $435 \text{ J/Kg } ^\circ\text{C}$ ($0.104 \text{ BTU/lb } ^\circ\text{F}$) [22].

Heat Treatments

To investigate how mechanical properties affect ballistic properties, it was desirable to vary the mechanical properties as much as possible. It has been shown that annealed versus aged In-718 yield vastly differing mechanical properties [19]. A small heat treatment study was performed on the 1.8 mm thick material to verify this range of properties. Several rectangular, flat tensile specimens, 150 mm in length by 12.7 mm wide were heat treated to one of several heat treatments shown in Table 2.

The specimens were tested at room temperature in a servohydraulic test machine. They were first run in strain control at a strain rate of 0.001/sec. The specimens were loaded up to a strain of 1.9 percent, and then unloaded to zero load. Strain was measured using a 12.7 mm gage length extensometer. These strain measurements allowed an accurate determination of the elastic modulus and the yield points. A diametral extensometer was also used to measure the transverse strain to enable calculations of Poisson's ratio. After the unload, the extensometers were removed and the specimen was loaded to failure in stroke control. A loading rate of 0.076 mm/sec was used. Failure strain was calculated based on a crosshead displacement over a 25.4 mm gage length and was simply the change in length divided by the original length.

The tensile curves are shown in Fig. 1. The data fell into two categories; moderate strength and high strain to failure (annealed), and high strength with moderate ductility (aged). Based on the results of these tensile tests, the three conditions A, B and C, shown in Table 3, were chosen for use with the ballistic impact tests. In addition, impact test results were compared with those from a previous study [20] on the same material. In the study of Ref. 20, the material was treated as shown by condition D in Table 3. The microstructure of the In-718 plates consisted of equiaxed grains (Fig. 3) with occasional carbide particles. The average grain sizes were an ASTM 6 for the 1.0 mm, ASTM 4 for the 1.8mm, and ASTM 9 for the 2.0 mm thick materials. The annealed and aged materials of the same thickness had identical grain sizes.

The tensile properties for heat treatments A, B and C are given in Table 4. Note that the 0.2 percent yield strength of the aged material is approximately three times that of the annealed, the UTS of the aged is one and a half times that of the annealed, while the ductility of the annealed material is substantially greater than the aged material. Note also the large difference in hardness values; the annealed material is softer. These differences in properties are sufficiently large to allow us to assess any possible effects of tensile properties on ballistic impact behavior. In fact, it would be difficult to find a material which exhibited such a wide range of tensile properties without completely embrittling the alloy and rendering it unsuitable for engineering purposes.

In a separate study, quasi-static and high strain rate compression testing was conducted on In-718 in conditions A and C [21]. These tests were conducted using a 19 mm diameter split Hopkinson Bar. Specimens were circular disks with a diameter of 6.35 mm and a thickness of 3.18 mm. Tests were conducted in the strain range of 1600 to 5000 /sec. The results of these tests are shown in Fig. 2. Like the quasi-static tensile data there is a marked difference in the response of the material in the two conditions. An important feature is the significantly greater strain hardening behavior of the material in the annealed condition.

TABLE 1.—COMPOSITION OF In-718 PLATES (wt. %)

Thickness, mm	Ni	Fe	Cr	Nb	Mo	Ti	Al	Mn	Si	Ta	Co	C
1.0	52.8	balance	18.2	5.05	2.98	1.03	0.51	0.22	0.14	<0.05	0.11	0.05
1.8	52.3	balance	18.2	5.11	3.04	1.05	0.50	0.22	0.14	<0.05	<0.05	0.05
2.0	52.7	balance	18.4	5.13	3.06	1.00	0.54	0.10	0.08	0.02	0.08	0.04

TABLE 2.—HEAT TREATMENTS USED FOR STATIC TESTING

Annealing conditions	
(1)	Annealed at 1037 °C/1h in vacuum + quick cool in argon
(2)	Annealed at 954 °C/1h in vacuum + quick cool in argon
(3)	Mill-annealed (as-received condition)
Aging conditions	
Anneal (1) + 718 °C/8h	in vacuum, cool at 38 °C/h to 621 °C, hold at 621 °C/8h, quick cool in argon
Anneal (2) + 718 °C/8h	in vacuum, cool at 38 °C/h to 621 °C, hold at 621 °C/8h, quick cool in argon
Anneal (1) + 760 °C/6h	in vacuum + quick cool in argon
Anneal (2) + 760 °C/6h	in vacuum + quick cool in argon

TABLE 3.—ANNEALING AND AGING CONDITIONS CHOSEN FOR IMPACT TESTING

Heat treatment designation	Condition
A	Annealed at 1037 °C/1h (vac.) + quick cool
B	As received condition (mill-annealed)
C	A + 718 °C/8h (vac.), cool at 38 °C/h to 621 °C, hold at 621 °C/8h, quick cool
D ^a	B + 718 °C/8h, cool at 38 °C/h to 621 °C, hold at 621 °C/8h, air cool

^aHeat treatment used with 350x350 mm panels from Ref. [20].

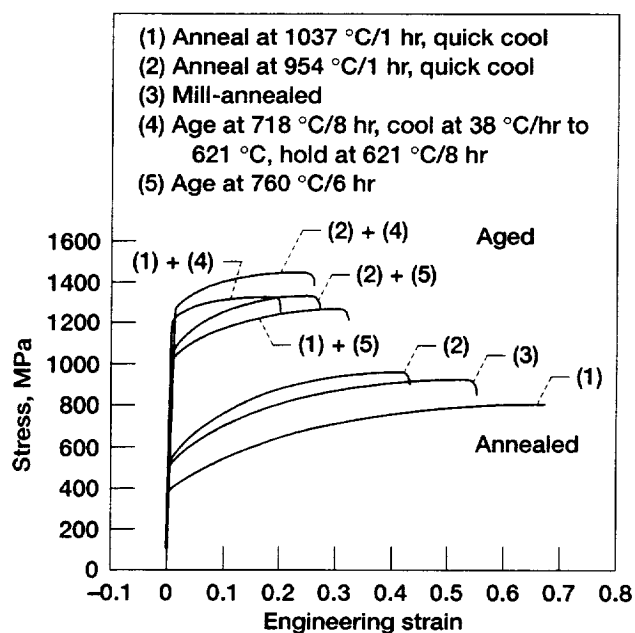


Figure 1.—Effect of heat treatment on the room temperature tensile behavior of In-718 sheet specimens.

TABLE 4.—MECHANICAL PROPERTIES OF TENSILE SPECIMENS

HT designation	Modulus, E, GPa	Poisson's ratio	YS _{0.2%} , MPa	UTS, MPa	Engineering Failure strain, percent	Reduction in area, percent	Hardness HRB (HRC)
A	198	0.29	331	821	67	46	84 (-)
B	198	0.28	483	924	55	43	96 (-)
C	205	0.26	1117	1338	20	30	114 (45)

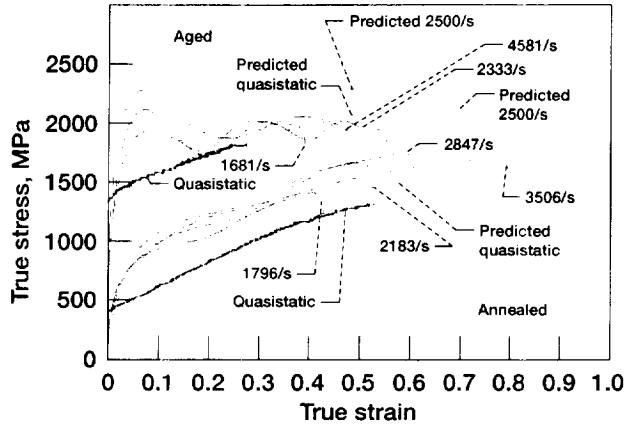


Figure 2.—Effect of heat treatment on the room temperature quasi-static and high strain rate compression behavior of In-718 from ref. 21. Also shown is the stress-strain behavior of the two material conditions predicted by the Johnson-Cook model for the quasi-static case and for a strain rate of 2500/s.

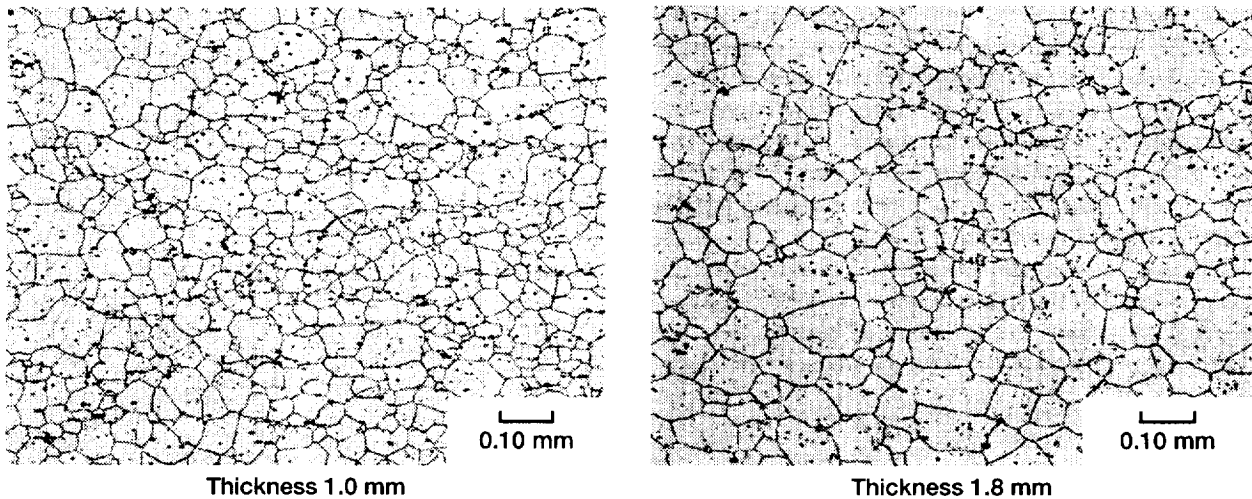


Figure 3.—Microstructure of Inconel 718 after annealing at 1038 °C.

The data of Fig. 2 were used to determine the room temperature material constants for the strength component of the Johnson-Cook model [22] for the In-718 in the two different conditions. The Johnson-Cook model is an empirically based representation of the flow stress defined as

$$\sigma = [A + B\varepsilon^n][1 + C \ln \dot{\varepsilon}^*][1 - T^{*m}] \quad (1)$$

where σ is the flow stress, ε is the effective plastic strain, $\dot{\varepsilon}^*$ is the effective plastic strain rate, usually normalized to a strain rate of 1.0/s, n is the work hardening exponent and A , B , C and m are constants. T^* is defined as

$$T^* = (T - 298)/(T_{melt} - 298) \quad (2)$$

where T is the temperature in Kelvin and T_{melt} is the melting temperature of the material. At room temperature $T^* = 0$.

For the annealed material, the parameters were determined to be $A = 400$ MPa, $B = 1798$ MPa, $n = .9143$, and $C = .0312$. For the aged material the parameters were determined to be $A = 1350$ MPa, $B = 1139$ MPa, $n = .6522$ and $C = .0134$. Figure 2 shows the correlation between the Johnson-Cook model with the above constants and the quasi-static tensile data. Also shown is the predicted response from the model at a strain rate of 2500/s.

BALLISTIC IMPACT TESTING

During impact of a containment system by a fan blade large structural deformations occur. To study any relationships that may exist between material properties and impact response relevant to the problem at hand, the target and projectile dimensions and velocities used in this study were selected to allow relatively large structural deformations while maintaining a controlled experiment. Ballistic impact tests were conducted on specimens of all three thicknesses shown in Table 1. The 1.0 and 1.8 mm impact specimens were treated according to the three conditions shown in Table 3. The 2.0 mm impact specimens were only tested in the mill annealed condition (Condition B). The impact specimens were 17.8 cm (7 in.) square panels and were centered and clamped over a 15.24 cm (6 in.) square hole in a 1.27 cm (0.5 in.) thick steel plate. Typical impact specimens are shown in Fig. 4. Specimens used in Ref. 20 were 35.5 cm (14 in.) square panels, centered and clamped over a 30.5 cm (12 in.) square hole in a 1.27 cm (0.5 in.) thick steel plate.

The projectile used in the present study and in Ref. 20 was a Ti-6-4 cylinder with a length of 2.54 cm (1 in.) and a diameter of 1.27 cm (0.5 in.). The impacting face was flat with a radius of 0.8 mm (1/32 in.) machined around the perimeter of the impacting surface. The hardness of the projectile was 32 HRC and its mass was in the range of 14.05 to 14.20 gm. The projectiles were accelerated toward the specimens at normal incidence using a gas gun with a 1.8 m (6 ft) long, 1.27 cm (0.5 in.) inner diameter barrel shown in Fig. 5. The ballistic limit for each heat treatment condition and thickness was determined by conducting a number of impact tests, typically seven, which bracketed as closely as possible the velocity required to penetrate the specimen. The ballistic limit was chosen, somewhat arbitrarily, to be approximately the average of the highest velocity for which no penetration occurred, and the lowest velocity at which penetration occurred. It is estimated that the error in the ballistic limit is within ± 6 m/sec (~ 3 percent). A measure of the extent of the impact damage was made by placing the panel on a surface plate and measuring the height of the permanent deformation in the damage zone. The height of the permanent deformation was either the height of the edge of the hole, if penetration occurred, or the maximum height of the dent if penetration did not occur. This measurement will henceforth be called deflection. Some of the specimens were sectioned and mounted for metallographic examination. In addition, microhardness measurements were made in the large deformation areas of the specimens. Standard polishing techniques were used for the In-718. However, due to the intense nature of the deformation, a special etching procedure was developed to reveal the deformation without burning the surface. The following etching procedure was used: Electrolytically etch at 4V in a solution of 10 g CrO_3 + 100 ml water. Remove stains by swabbing with Tucker's reagent. Repeat as needed.

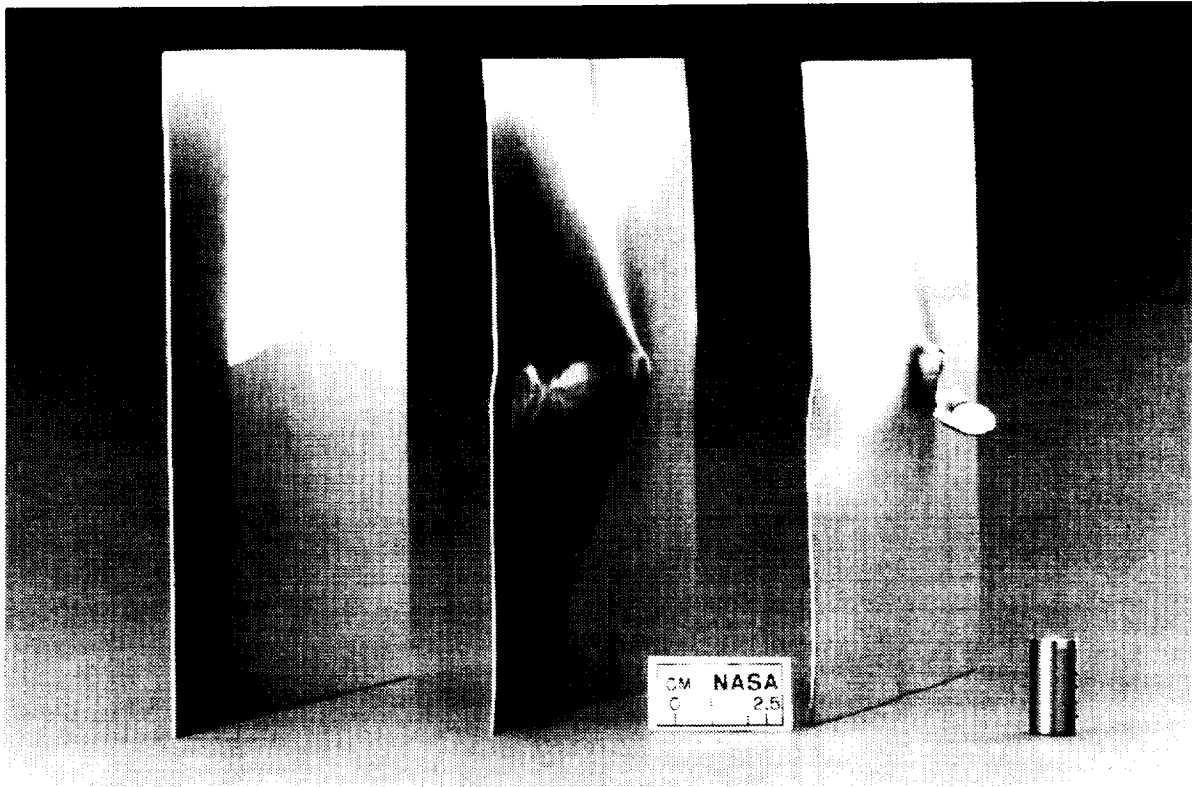


Figure 4.—Typical test specimens in the initial, nonperforated and perforated conditions.

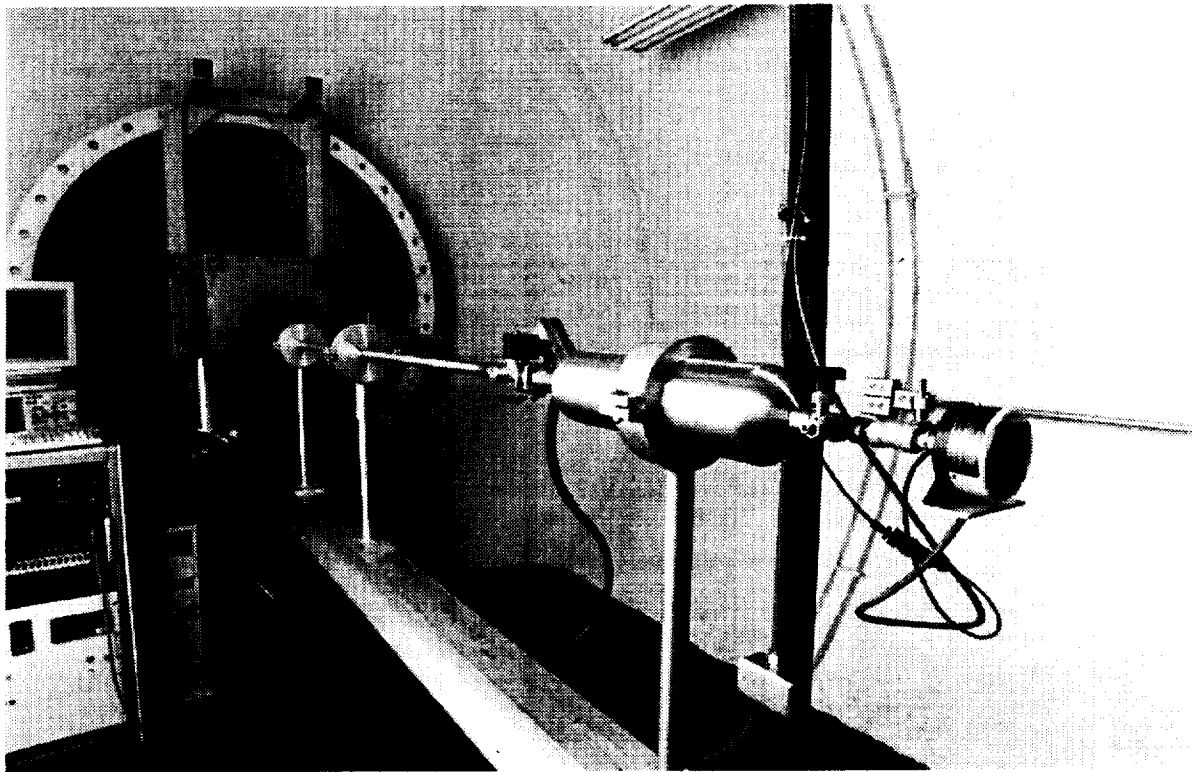


Figure 5.—50 caliber gas gun facility.

RESULTS

For the initial heat treatment study, the quasi-static stress-strain curves fell into two groups (Fig. 1). The annealed material exhibited moderate strength and high elongation while the annealed plus aged material exhibited high strength and moderate elongation. The hardness for these materials was measured to be ~90 HRB for the soft, annealed materials and 45 HRC for the harder, aged materials (C and D). The figure includes the three conditions used in the subsequent impact tests, as well as the heat treatment condition used in Ref. 20. It should be noted that the curve in Fig. 1 designated by "(2) + (4)" was taken from tests on the material from the present study heat treated in the same way as in Ref. 20. However, it is expected that the material with condition D used in Ref. 20 would have a similar response to this.

TABLE 5.—IMPACT TEST RESULTS

Spec. ID	Thickness, mm	Heat treat condition	Rockwell hardness	Deflection height, h, mm	Damage type	Impact velocity, m/sec
GA70	1.83	Annealed	95 HRB	18.0	Perforated	281
GA71	1.83	Annealed	95 HRB	18.0	Perforated	275
GA72	1.85	Annealed	95 HRB	17.9	Perforated	273
GA73	1.80	Annealed	95 HRB	20.0	Non	258
GA74	1.85	Annealed	95 HRB	17.8	Perforated	269
GA75	1.80	Aged	45 HRC	10.8	Perforated	258
GA76	1.83	Aged	45 HRC	9.4	Perforated	248
GA77	1.85	Aged	45 HRC	9.9	Non	226
GA78	1.80	Aged	45 HRC	10.9	Non	243
GA79	1.83	Aged	45 HRC	9.2	Perforated	245
GA60	1.04	Annealed	95 HRB	23.6	Non	190
GA61	1.07	Annealed	95 HRB	23.9	Non	192
GA63	1.04	Annealed	95 HRB	23.6	Non	193
GA64	1.12	Annealed	95 HRB	25.0	Non	198
GA62	1.04	Annealed	95 HRB	14.3	Perforated	200
GA65	1.04	Aged	45 HRC	8.4	Perforated	187
GA66	1.07	Aged	45 HRC	10.3	Perforated	175
GA67	1.04	Aged	45 HRC	10.2	Non	167
GA68	1.12	Aged	45 HRC	10.4	Non	172
GA69	1.09	Aged	45 HRC	9.2	Perforated	166
GA87	2.06	Mill Anneal	82 HRB	11.7	Perforated	297
GA88	2.06	Mill Anneal	82 HRB	14.8	Non	262
GA89	2.06	Mill Anneal	82 HRB	16.5	Non	281
GA90	2.03	Mill Anneal	82 HRB	15.5	Perforated	284

TABLE 6.—BALLISTIC LIMIT FOR In 718

Heat treatment	Areal weight, kg/m ²	Ballistic limit velocity, m/sec	Ballistic impact energy, J
A	8.35	198	277
A	14.60	265	497
B	8.35	192	260
B	14.60	277	543
B	16.70	282	562
C	8.35	168	198
C	14.60	244	420
D	8.35	171	206
D	14.60	241	409

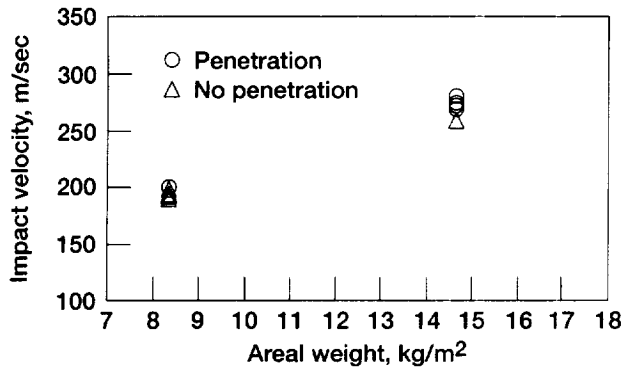


Figure 6.—Impact velocity and penetration results for Inconel 718 annealed at 1038 °C—Condition A.

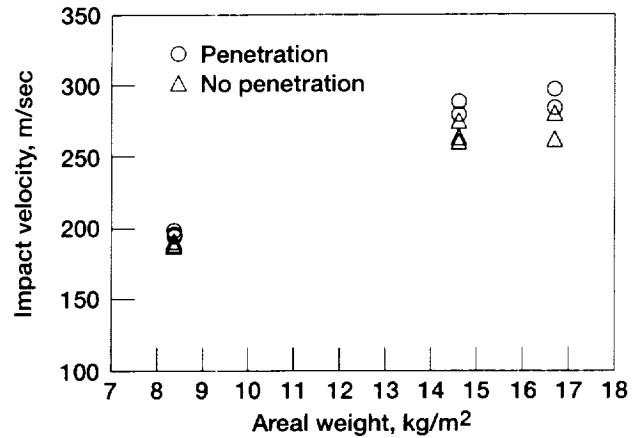


Figure 7.—Impact velocity and penetration results for Inconel 718 in the as-received condition—Condition B.

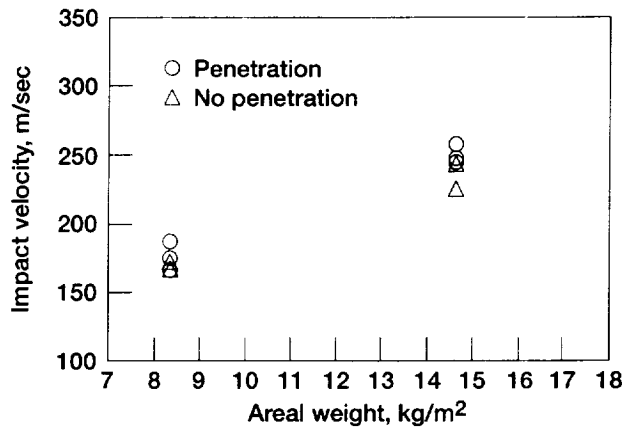


Figure 8.—Impact velocity and penetration results for aged Inconel 718—Condition C.

Table 5 lists the velocities and results of the impact tests, as well as a measure of the resulting deflection that occurred. Impact test velocities for each of the thickness and heat treatment conditions is shown in Figs. 6 to 8. The ballistic limit for each condition extracted from these data is shown in Table 6, and includes the ballistic limit for heat treatment D, taken from Ref. 20. In this table, areal weight refers to the weight per unit area of the material, or simply the product of the density and the thickness. This is a relevant measure for fan containment systems since, in general, the overall geometry of the system will be similar, irrespective of the material used. A plot of these data is shown in Fig. 9 and includes the penetration velocity for the 2 mm thick plate in the mill annealed condition (B). For all thicknesses, the annealed material with a lower hardness, moderate strength and higher elongation had superior impact energy absorbing properties compared to the aged material with a higher hardness, higher strength and moderate elongation. For the 1.0 mm thick specimens there was an average increase of 33 percent in the ballistic impact energy of the annealed over the aged material. For the 1.8 mm thick material the average increase was 25 percent. This is contradictory to results in the literature for high velocity impacts [3 and 4] where it was found that high hardness materials exhibited greater impact resistance.

Metallographic examination of the specimens showed that for both sets of heat treating conditions, the impact produced a circular band of shear deformation extending from the corners of the projectile at the impacted surface to the back surface of the plate at an angle of roughly 45° from the plate normal (Fig. 10). There was significantly more overall deformation in the annealed specimens than the aged specimens as shown by the amount of deflection

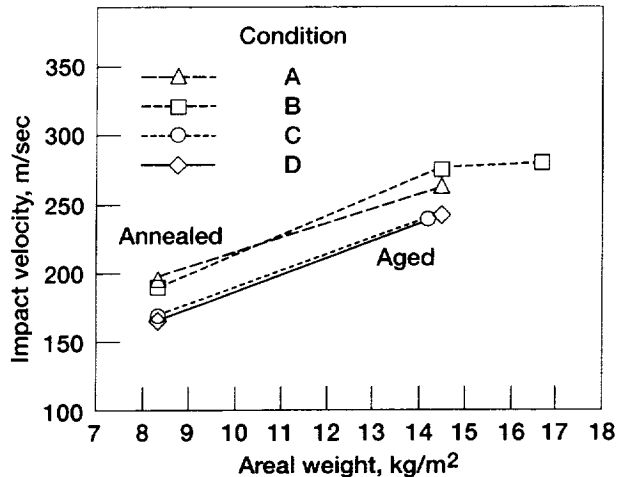


Figure 9.—Impact velocity and penetration results for Inconel 718 as a function of areal weight and heat treatment.

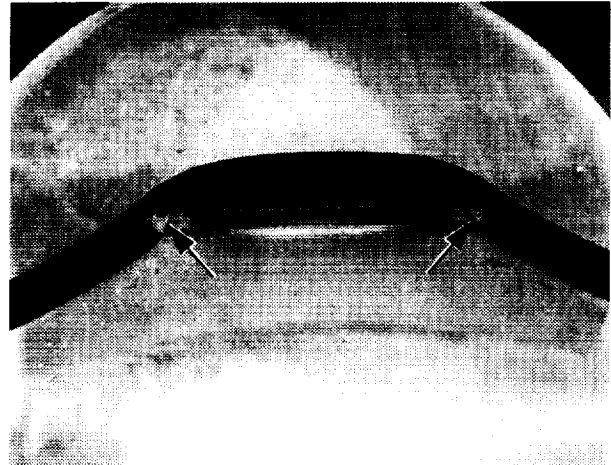


Figure 10.—Shear deformation pattern in impacted specimen.

in Fig. 11. There was essentially no permanent deformation in the projectiles. Microscopic examination (Fig. 12(a)) showed that the annealed specimen exhibited what appeared to be an intense deformation band originating from the corner of the projectile impact. This band was somewhat ill-defined in structure and extended in width over ~10 grains. In nonperforated samples, the band did not reach the back face of the plate. A higher magnification of this band (Fig. 12(b)) shows that this was not a true band, but rather a collection of intensely deformed grains, which etched darker than the surrounding grains. The surrounding grains were also heavily deformed, but not to the extent of those in the band. A microhardness profile was taken across the band. Vicker's hardness ranged from ~260 (100 HRB) in areas far removed from the band (yet still in the deformed region) to a hardness of ~400 (41 HRC) in the band itself.

The aged samples had a much finer deformation structure as shown in Fig. 13. Attempts to bring out visible shear bands were limited. This was partially due to the multitude of fine slip bands in each grain and partially due to the poor etching characteristics of the aged samples. At areas of intense shear (i.e., projectile impact corners), some evidence of well-defined macroscopic bands was observed, but these were generally short and narrow, often connecting carbide particles. Compared to the apparent bands observed in the annealed material (Fig. 12), the bands in the aged material were much narrower, and often multiple bands could be observed in one grain. Similar microhardness profiles were performed with similar results to those in the annealed material. However, the hardness values were higher in all locations due to the fact that the material was originally aged. The hardness ranged from 400 (41 HRC) remote from the shear zone to 500 (49 HRC) in the shear zone.

Close examination of the back surface of both the aged and annealed materials revealed shear bands at 45° angles to the surface of the plate and at multiple locations near the plug. Shear bands caused a V-notch at the surface of the plate (Fig. 13). In specimens that were not perforated, cracks were observed emanating from the notches and propagating along the shear bands. These were the only evidence of cracking in the nonperforated specimens. Similar notches and shear bands have been observed in explosively bonded In-718 [23].

DISCUSSION

At high strain rates there is essentially no strain hardening in the aged In-718, as shown by the flat curves in Fig. 2. This differs from the quasi-static behavior which exhibits a good amount of strain hardening. This behavior is also different from the annealed material which has a large amount of strain hardening, even at high strain rates. The Johnson-Cook model was able to reproduce the quasi-static behavior of both material conditions and could predict the high strain rate data from the annealed material. However, the model was unable to predict the high strain rate data for the aged material.

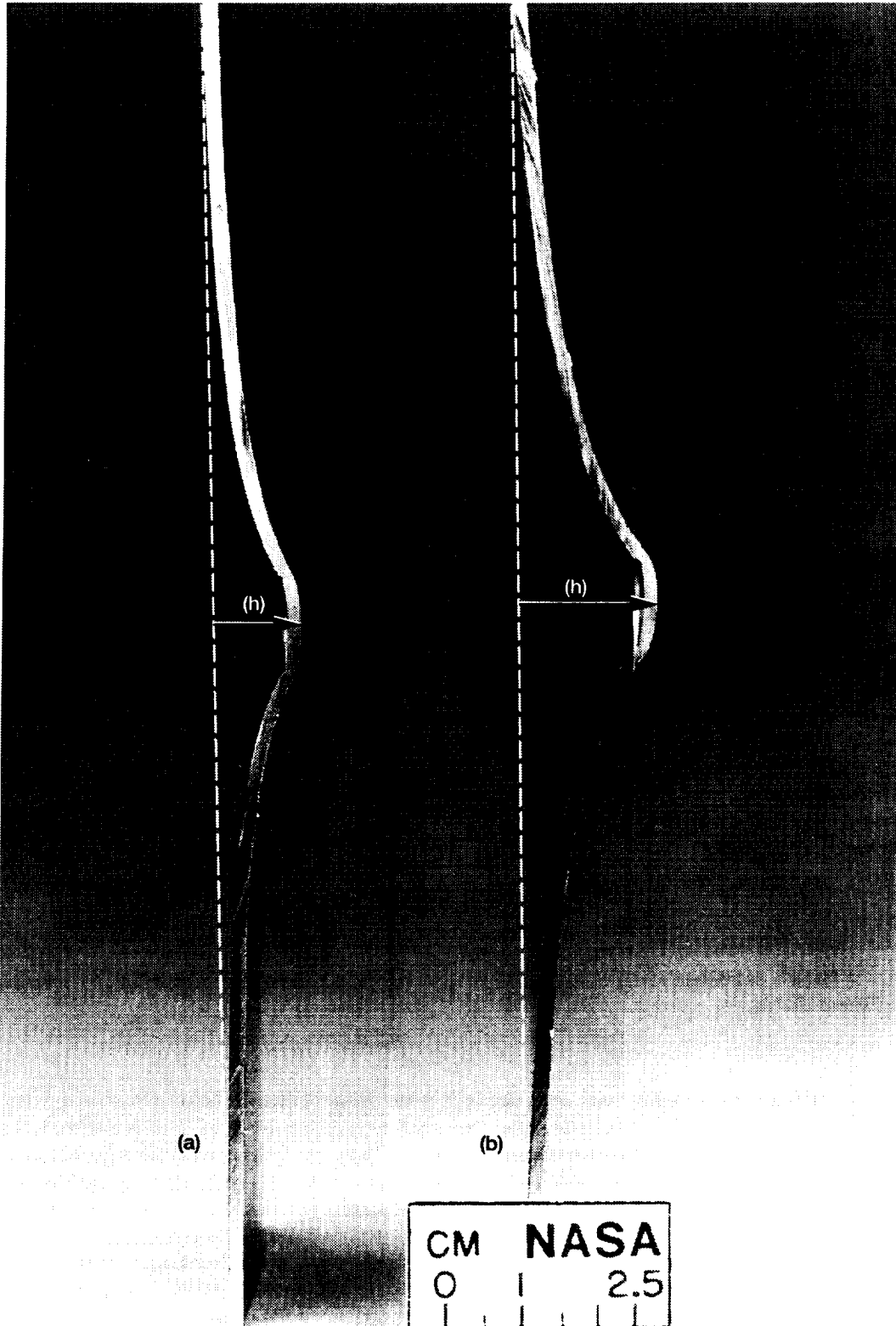


Figure 11.—a) Comparison of overall deformation in aged specimen. b) Annealed specimen. Each specimen was impacted at a velocity slightly below its ballistic limit.

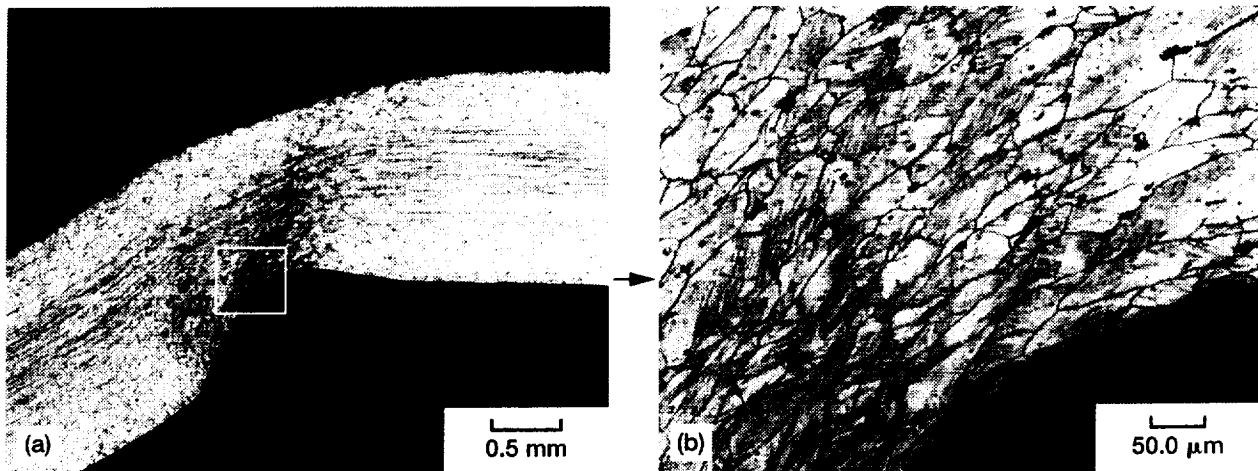


Figure 12.—a) Region of intense shear deformation in annealed specimen. b) Higher magnification shows a collection of intensely deformed grains rather than highly localized shear bands.

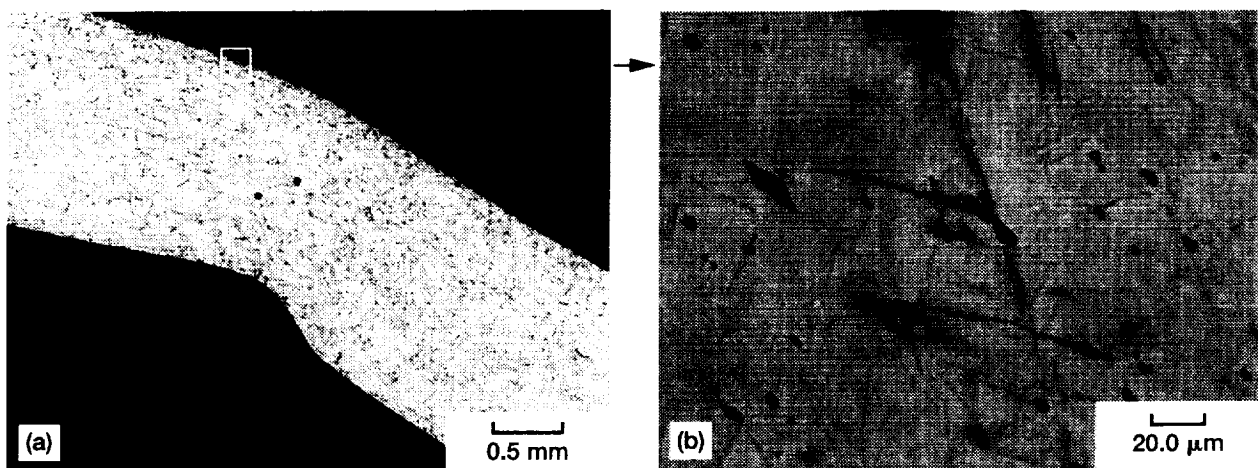


Figure 13.—a) Region of intense shear deformation in aged specimen. b) Higher magnification shows highly localized shear bands.

Under the conditions used in this study, annealed In-718 has greater impact resistance than the aged material. The annealed material can absorb more plastic deformation before penetration occurs. This is evident from the deflection measurements in Table 5 and shown visually in Fig. 11. The large deflections in the annealed specimens, as illustrated in Fig. 4 produced some undesirable features in the experiment. Because of the large deflections, the boundary conditions may have had some effect on the results. Preliminary tests using 15 and 30 cm apertures in the impact test fixture showed no significant differences in the measured ballistic limit, but the overall deflections could have been effected. Also, while the projectile impacted the specimen with normal incidence, failure in the specimen was not always symmetrical, and often a plug partially separated, forming a flap. This is illustrated in Fig. 4. While this may be an artifact caused by some interaction with the boundaries it is not unusual for this type of behavior to occur. Woodward [12] noted that in plugging failures several bands are observed to nucleate and propagate independently, leading to asymmetry in the failure region.

The static toughness, as measured by the area under the stress-strain curve, is greater for the annealed material than the aged, as shown in Fig. 1. The improvement in impact resistance of the annealed material is consistent with general guidelines for designing containment systems that correlate larger areas under the static stress-strain curve

with enhanced impact properties [18]. However, the improved impact resistance may be more related to the failure mechanisms rather than simply the area under the stress-strain curve. This measurement of toughness is different from a Charpy or K_{IC} fracture toughness, both of which deal with the energy required to propagate a crack. The area under the stress-strain curve is more related to the absorption of plastic deformation before failure and may not even involve a crack until the last moments of the tensile test. It should be pointed out that for In-718, Charpy impact results also showed that the annealed material is tougher than the aged [19]. Thus for In-718, Charpy values appear to correlate with ballistic toughness. However, is not the case for all materials, as illustrated by the results of Burkins and Love [6] who found no correlation between Charpy impact results and ballistic impact resistance in Ti-6-4.

The hardness of the Ti-6-4 projectile used in the impact tests was intermediate between that of the annealed and the aged target material. In general, the ballistic limit velocity decreases when the projectile hardness exceeds that of the target [24]. Therefore it is possible that these test results underestimate the greater effectiveness of the annealed over the aged material. However, the results are relevant to jet engine containment systems in which the fans are typically Ti-6-4.

The annealed material appears to better absorb energy by diffusing the macroscopic shear zone over a wider area (Fig. 12). Whereas Fig. 12 indicates that a diffuse macroshear band is formed, high magnification examination of this area revealed that bands *per se* are not formed. Instead, the grains in this area of intense shear are just more heavily deformed and therefore etch darker than the surrounding grains. This is also indicated by the microhardness profiles, which revealed a higher hardness in the "band" region, typical of more work hardening (plastic deformation) and agrees with hardness readings taken near shear bands in other materials [25 to 28]. At least at low magnification, these apparent bands appear similar to those observed in brass [29 and 30] and copper [30 and 31]. In these cases more homogeneous bands formed under isothermal conditions associated with necking during tensile tests. Broad and diffuse bands were also observed in copper under punch-loaded conditions [32].

In contrast, the aged material does show narrow shear bands, thus constricting the later stages of deformation to thin zones, typical of adiabatic shear bands [33]. It has been suggested [25 and 34] that shear localization increases with decreasing strain hardening and increasing strength, both of which are exhibited by the aged material. This would explain why the aged material has definite shear band formation and the annealed material does not. Additionally, aged In-718 deforms by the shearing of ordered precipitates [35]. During this process, the precipitates are reduced in size within the slip plane, as successive dislocations approach and shear the precipitates. Consequently, slip within this active plane is easier than on a neighboring inactive slip system. This would encourage shear bands to be narrow. The annealed In-718 does not have ordered precipitates and therefore slip on an existing system can only get more difficult due to dislocation tangles (work hardening). The zone of deformation spreads to neighboring, weaker planes forming a broad diffuse band. For adiabatic shear to occur, the amount of softening due to the local temperature increase must equal the rates of strain and strain rate hardening [36]. Softening can be assisted by precipitate shearing. The annealed material shows significantly greater strain hardening behavior under high strain rate conditions. Therefore, based on the above discussion, as well as the model of Bai and Johnson [16] discussed in the introduction, one would expect the aged In-718 to have more of a tendency to form adiabatic shear bands than the annealed.

Shear localization can also result from the geometry of the specimen and target and the constraints placed on them [34]. It can be seen in Fig. 9 that for the mill-annealed material, the increase in penetration velocity slowed as the thickness of the specimen increased. A possible explanation for this is that the greater bending stiffness of the thicker (2 mm) panel constrained the amount of deformation that could take place. This in fact can be seen by the reduction in the deflection measurements in Table 5. This result is consistent with the model of Bai and Johnson [16] which predicts that as the thickness of the plate increases, the energy absorbed per unit thickness begins to level off. Metallography revealed no difference in the deformation structure as these specimens also contained broad, diffuse bands just like the other annealed samples. The thickest material did have a smaller grain size (ASTM 9 compared to an ASTM 6 for the intermediate thickness), but this is not believed to have reduced the slope of the curve. It is possible that the reduction in the slope of the curve was simply experimental variation since the thick material was from a different study and was added here just for completeness. Examination of additional thicknesses, especially greater than 2.06 mm, would have helped to clarify whether the slope of the curve continues to increase with increasing thickness, or if it levels off as suggested in Fig. 9. However, the existing impact facility was unable to produce the velocities required to penetrate thicker plates.

Post test analysis of the deformation and fracture behavior of the plates suggest the following scenario. Upon impact, the flat-bottomed projectile compresses the material underneath it. Simultaneously, the plate is deflected in the direction of the impact. Bands of intense deformation form at the location of the projectile corners, but for sub-

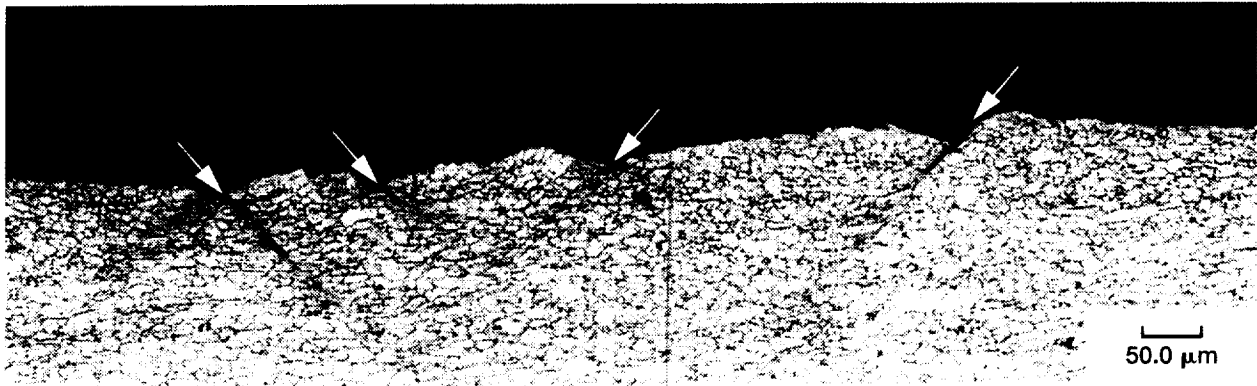


Figure 14.—Notches on back surface produced by high tensile stresses and the resulting shear bands.

critical velocities do not propagate completely through the thickness. On the back side, shear bands form causing notches on the surface (Fig. 14). Cracks often form within these bands probably due to the high tensile stresses on the back surface. Cracking presumably occurs from the front surface as well, but it was never observed in the nonperforated samples. One can assume that if the velocity is high enough to cause cracking on the front surface, the projectile will perforate the plate. Therefore, front side cracking could be used as a critical condition for predicting failure in these tests. Since the cracks on the back surface will also propagate, there is a competition between the front and back side cracks. This often led to a chiseled-shaped fracture surface. Jones et al. [13] observed similar failure behavior in aluminum alloys when impacted by flat faced cylindrical projectiles, where failure on the proximal surface lead to complete failure across the plate thickness. In contrast, they found that for mild steel, which has a high adiabatic shear strength [16], impact failure under similar conditions is dominated by material failure on the distal side.

SUMMARY

Under the conditions used in this study, the softer, annealed Inconel 718 performed significantly better than the harder aged material. This is in contrast to results in the literature for higher velocity impacts, which indicate that ballistic limit increases with hardness. The results presented here suggest that toughness may be a better predictor of ballistic impact resistance for the type of failure mechanism and impact velocity associated with fan containment events with Inconel 718. The results indicate that high elongation and better strain hardening capabilities reduce the tendency for shear to localize and result in an unstable adiabatic shear failure. This supports empirical containment design methods that relate containment thickness to the static toughness.

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