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Hydrostatic Extrusion of Metals and Alloys

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IN HYDROSTATIC EXTRUSION, the billet is extruded through a die via the action of a liquid pressure medium instead of the direct application of the load through a ram. In cases of hydrostatic extrusion, the billet is completely surrounded by a fluid. The fluid is then pressurized, and this provides the means to extrude the billet through the die. In order to review the various issues and benefits associated with hydrostatic extrusion, this article begins with a general review of the effects of changes in stress state on processing of materials. With this as a background, some of the fundamentals associated with hydrostatic extrusion are covered. This is followed by examples of materials processed via these means. This article closes with attempts to extend this processing technique to higher temperatures.

General Aspects of Stress-State Effects on Processing

A number of factors affect the deformability of a material such as strain rate, stress state, temperature, and flow characteristics of the material, which are affected by crystal structure and microstructure. Changes in stress state via the superimposition of hydrostatic pressure can clearly exert a dominant effect on the ability of a material to flow plastically, regardless of the other variables. In many forming operations, controlling the mean normal stress σ_m is critical for success (Ref 1, 2). Compressive forces that produce low values of σ_m increase the ductility for a variety of structural materials (Ref 3–24), while tensile forces that generate high values of σ_m significantly reduce ductility and often promote a ductile to brittle transition. Thus, metalforming processes, which impart low values of σ_m are more likely to promote deformation of the material without significant damage evolution (Ref 1, 2). There are a variety of industrially important forming processes that utilize the beneficial aspects of a negative mean stress on formability, such as extrusion, wire drawing, rolling, or forging. In such cases, the negative mean stress can be treated as a hydrostatic pressure that is imparted by details of the process (Ref 1, 2). More direct utilization of hydrostatic pressure includes the densification of porous powder metallurgy products where both cold isostatic pressing (CIP) and hot isostatic pressing (HIP) are utilized. In addition, many superplastic-forming operations conducted at intermediate to high homologous temperatures utilize a backpressure of the order of flow stress of the material in order to inhibit/eliminate void formation (Ref 25–27). Pressure-induced void inhibition in this case increases the ability to form superplastically in addition to positively impacting properties of the superplastically formed material.

While it is clear that triaxial stresses are present in many industrially relevant forming operations, the mean stress may not be sufficiently low to avoid damage in the form of cavities and cracks. In these cases, σ_m can be lowered further by superimposing a hydrostatic pressure. Articles and books highlighting such techniques are provided (Ref 1, 2, 28–51).

Some of the key findings and illustrations are summarized to highlight the importance and effects of hydrostatic pressure, whether it arises due to die geometry or is superimposed, via a fluid, on formability. Various textbooks (Ref 1, 2) and articles (Ref 50, 51) have reviewed the factors controlling the evolution of hydrostatic stresses during various forming operations. In strip drawing, the hydrostatic pressure ($P = -\sigma_2$) varies in the deformation zone and is affected by both the reduction (r) as well as the extrusion die angle (α) as shown in Fig. 1 and 2. Both figures illustrate that the mean stress (represented by σ_2) may become tensile (shown as negative values in Fig. 1 and 2) near the centerline of the strip. Furthermore, both the distribution and magnitude of hydrostatic stresses are controlled by α and r, with the level of hydrostatic tension at the centerline varying with α and r in a manner illustrated in Fig. 2.

Consistent with previous discussions on the effects of hydrostatic pressure on damage, it is clear that processing under conditions that promote the evolution of tensile hydrostatic stresses will promote the formation of internal damage in the product in the form of microscopic porosity at and near the centerline. In extreme cases, this takes the form of internal cracks. A significant decrease in density (due to porosity formation) after slab drawing has been recorded (Ref 50, 51), particularly in material taken from near the centerline. This is generally consistent with the levels of tensile hydrostatic pressure present as predicted in Fig. 1 and 2. Furthermore, it was found that a greater loss in density occurred with smaller reductions (i.e., small r) and higher die angles (i.e., larger α), consistent with Fig. 2. Such damage will reduce the mechanical and physical properties of the product.

It has been found that the loss in density in a 6061-T6 aluminum alloy could be minimized, or prevented, by drawing with a superimposed hydrostatic pressure, as shown in Fig. 3 (Ref 51). In some cases, increases in the strip density were recorded, apparently due to an elimination of porosity, which was either present or evolved in the previous processing steps. It is clear that maintaining a compressive mean stress will increase formability, regardless of the forming operation under consideration.

Materials with limited ductility and formability can be extruded, as demonstrated below for a variety of composites (Ref 18, 28, 32, 37, 52, 53) and the intermetallic NiAl (Ref 54–56), if both the billet and die exit regions are under high hydrostatic pressure. Figures 1 and 2 illustrate that, in the absence of a beneficial stress state, large tensile hydrostatic stresses can evolve in forming operations that are conducted under nominally compressive conditions. Thus, it should be noted that the example of strip drawing provided is relevant to other forming operations such as extrusion and rolling where similar effects have been observed along the centerline of the former and along the edges of rolled strips in the latter. During forging or upsetting, barreling due to frictional effects causes the tensile hoop stresses to evolve at the free surface and can promote fracture at these locations (Ref 1, 2, 57, 58).

The remainder of this article focuses on a specific procedure that utilizes an approach to enable deformation processing of materials at low homologous temperatures, that is, hydrostatic extrusion (Ref 30, 31, 59–72). The beneficial stress state imparted by such processing conditions enables deformation processing to be conducted at temperatures below those at which recovery processes occur (e.g., recovery, recrystallization) while minimizing the amount of damage imparted to the billet material. Such processing is used in the production of wire, while concepts covered below are generally applicable to the various forming operations and specifically those dealing with extrusion.

Hydrostatic Extrusion Fundamentals

Hydrostatic extrusion involves extruding a billet through a die using fluid pressure instead of a ram, which is used in conventional extrusion. Figure 4 compares conventional extrusion with hydrostatic extrusion, the main difference being the amount of billet/container contact (Ref 34). In hydrostatic extrusion, a billet/fluid interface replaces the billet/container interface present in conventional extrusion. The three main advantages of hydrostatic extrusion are:

- The extrusion pressure is independent of the length of the billet because friction at the billet/container interface is eliminated.
- The combined friction of billet/container and billet/die contact reduces to billet/die friction only.
- The pressurized fluid gives lateral support to the billet and is hydrostatic in nature outside the deformation zone, preventing billet buckling. Skewed billets have been successfully extruded under hydrostatic pressure (Ref 33).

There are limitations inherent in hydrostatic extrusion. The use of repeated high pressure makes containment vessel design crucial for safe operation. The presence of fluid and high-pressure seals complicates loading, and fluid compression reduces the efficiency of the process.

A typical ram-displacement curve for hydrostatic extrusion versus conventional extrusion is shown in Fig. 5. The initial part of the curve for hydrostatic extrusion is determined by fluid compressibility as it is pressurized. A maximum pressure is obtained at billet breakthrough, at which point the billet is hydrodynamically lubricated and friction is lowered (static to kinematic). The pressure drops to an essentially constant value, called the run-out or extrusion pressure. Finally, the fluid is depressurized to remove the extruded product. Higher pressures are typically required in conventional extrusion due to increased friction between the billet and die, as shown in Fig. 4 and 5 (Ref 34).

Hydrostatic extrusion can be conducted via extrusion into air or extrusion into a receiving pressure. The latter process has been shown to help to prevent billet fracture on exit from the die for a range of conventional and advanced structural materials including metals (Ref 35, 36, 73, 74), metal-matrix composites (Ref 18, 28, 29, 32, 41–43, 75), and intermetallics (Ref 54, 56, 76, 77).

Occasionally, "stick-slip" behavior is observed due to lubrication breakdown and recovery, in which case the run-out pressure fluctuates both above and below the steady-state value. Stick-slip causes a variation in product diameter and represents an instability in the process. Strong billet materials, large extrusion ratios, and slow extrusion rates facilitate this type of undesirable behavior. The use of viscous dampers, or reducing the hydrostatic fluid used, can eliminate "stick-slip" behavior.

The work done per unit volume in hydrostatic extrusion is equal to the extrusion pressure P_{ex} (Ref 34). The four parameters that control the magnitude of P_{ex} are die angle, reduction of area (extrusion ratio), coefficient of friction, and yield

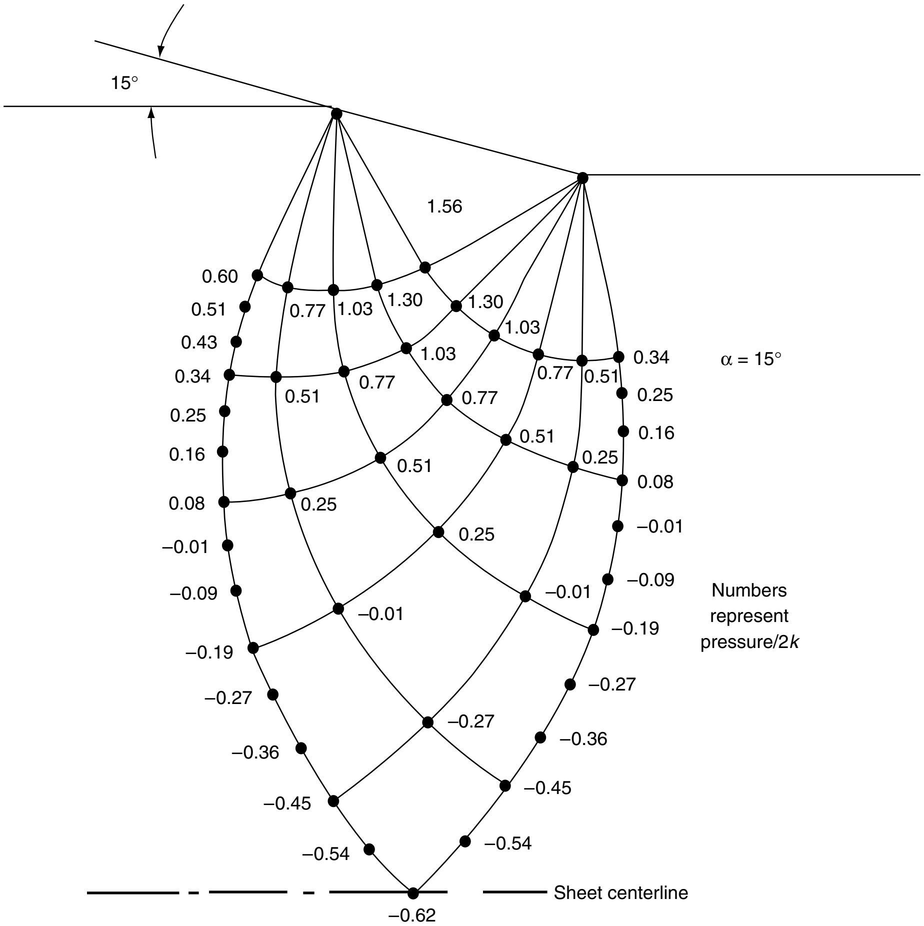

Fig. 1 Variation in hydrostatic pressure for strip drawing of sheet. Negative values represent tensile stresses. Source: Ref 50

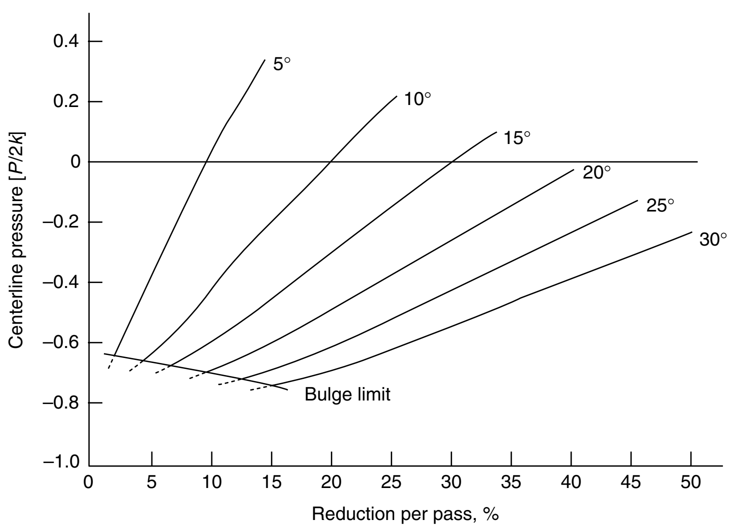

Fig. 2 Pressure variation at centerline of strip for various combinations of r and α during strip drawing. Negative values indicate hydrostatic tensile stresses. Source: Ref 50

strength of the billet material. There are three types of work incorporated into extrusion pressure: work of homogenous deformation, or the minimum work needed to change the shape of the billet into final product; redundant work, because of reversed shearing in the deformation zone; and work against friction at the billet/die interface (Ref 34). As die angle is increased, the billet/die interface decreases reducing the friction force, but the amount of redundant work increases. Therefore, die angle is a parameter that must be optimized for an efficient process, as shown in Fig. 6.

For a given die angle, increased extrusion ratios yield higher billet/die interfacial areas, as schematically shown in Fig. 7. Consequently, higher extrusion ratios require larger extrusion pressures to overcome increased work hardening in the billet region because of the larger strains. Higher coefficients of friction and billet yield strengths will cause an increase in extrusion pressure.

Mechanical analyses of hydrostatic extrusion have been performed by Pugh (Ref 31) and Avitzur (Ref 30, 33). In both analyses, assumptions are made that the material does not experience deformation parallel to the extrusion axis, but undergoes shearing and reverse shearing (fully homogeneous) on entry and exit of the die. Pugh's efforts resulted in Eq 1, which assumes a work-hardening billet material, and a condensed version (Eq 4), which considers a non-work-hardening material. The result of Pugh's analyses are:

$$P_{ex} = \int_{0}^{\varepsilon_3} \sigma_{flow} d\varepsilon + \frac{\mu R_{ex} \ln R_{ex}}{\sin\alpha (R_{ex} - 1)} \int_{\varepsilon_1}^{\varepsilon_2} \sigma_{flow} d\varepsilon \quad \text{(Eq 1)}$$

where

$$\varepsilon_1 = 0.462 \; [(\alpha/\sin^2 \alpha) - \cot \alpha] \quad \text{(Eq 2)}$$

$$\varepsilon_2 = \varepsilon_1 + \ln R_{ex}, \; \varepsilon_3 = \varepsilon_1 + \varepsilon_2 \quad \text{(Eq 3)}$$

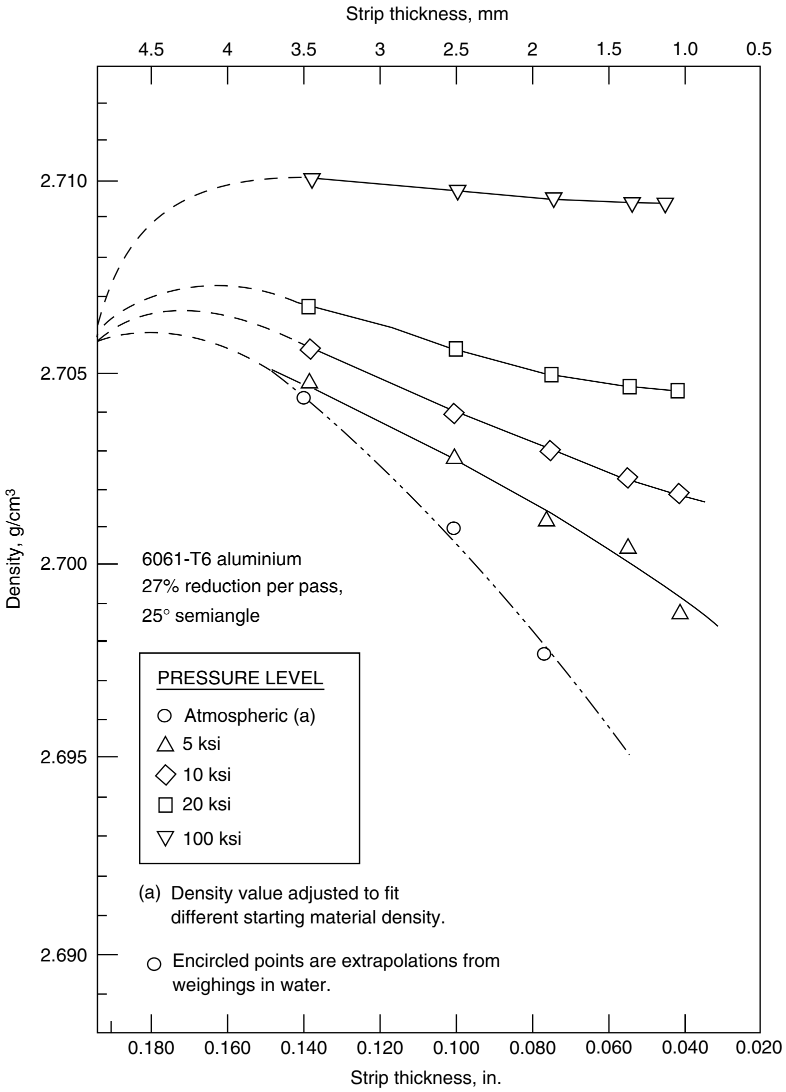

Fig. 3 Effects of superimposed pressure on density loss, measured after strip drawing. Increased pressure reduces density loss due to inhibition of nucleation/growth of microporosity. Source: Ref 51

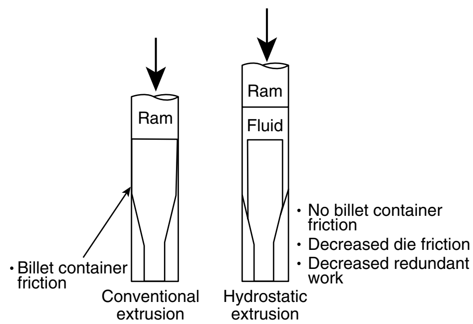

Fig. 4 Comparison of conventional extrusion and hydrostatic extrusion. Source: Ref 28, 66

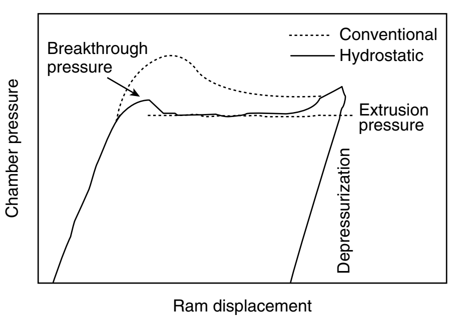

Fig. 5 Typical ram-displacement curves for extrusion. Source: Ref 34

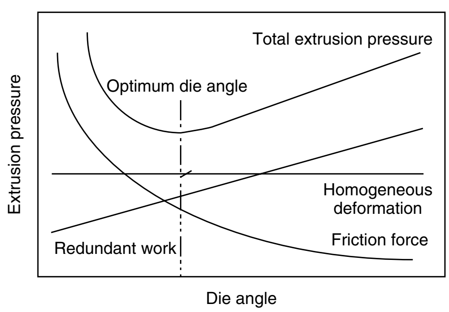

Fig. 6 Effects of changes in die angle on extrusion pressure. Source: Ref 34

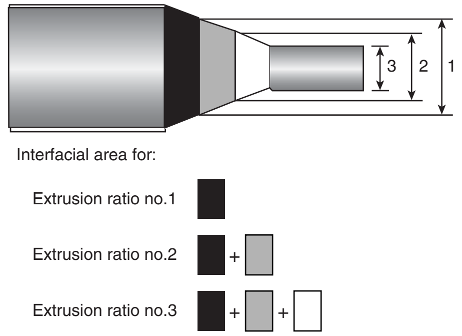

Fig. 7 Effect of extrusion ratio on billet/die container contact area. Source: Ref 28, 34

$$\frac{P_{ex}}{\sigma_B} = 0.924\left[\frac{\alpha}{\sin^2\alpha} - \cot\alpha\right] + \ln R_{ex}\left[1 + \frac{\mu R_{ex}\ln R_{ex}}{\sin\alpha\,(R_{ex}-1)}\right] \quad \text{(Eq 4)}$$

where P_{ex} is the extrusion pressure in MPa, R_{ex} is the extrusion ratio, α is the extrusion die angle in radians, μ is the coefficient of friction, σ_{flow} is the flow stress, and σ_B is the yield strength of the billet material in MPa.

Avitzur's analysis produced Eq 5 with the assumption that the billet material is not work hardening. The analysis yielded:

$$\frac{P_{ex}}{\sigma_B} = \frac{2}{\sqrt{3}}\left[\frac{\alpha}{\sin^2\alpha} - \cot\alpha\right] + f(\alpha)\ln R_{ex} + \mu\cot\alpha\,(\ln R_{ex})\left[1 + \frac{\ln R_{ex}}{2}\right] \quad \text{(Eq 5)}$$

where P_{ex} is the extrusion pressure in MPa, R_{ex} is the extrusion ratio, α is the extrusion die angle in radians, μ is the coefficient of friction, and σ_B is the yield strength of the billet material in MPa. The quantity $f(\alpha)$ is given by:

$$f(\alpha) = \frac{1}{\sin^2\alpha}\left[\left[1 - \cos\alpha\sqrt{1 - \frac{11}{12}\sin^2\alpha}\right] + \frac{1}{\sqrt{11/12}}\ln\left[\frac{1 + \sqrt{\frac{11}{12}}}{\sqrt{\frac{11}{12}}\cos\alpha + \sqrt{1 - \frac{11}{12}\sin^2\alpha}}\right]\right] \quad \text{(Eq 6)}$$

These equations can be used to predict extrusion pressure for a variety of conditions. Prediction of extrusion pressure is convenient for apparatus/billet design and necessary for safety during operation. Comparisons of these models to some recent experiments on composites are provided below.

Hydrostatic Extrusion of Structural Alloys

A variety of materials have been successfully processed via hydrostatic extrusion, as summarized in Table 1 (Ref 30, 31, 59–72) where the die angle as well as the billet hardness before and after hydrostatic extrusion are recorded. Much of the early work utilizing such techniques is summarized in various review papers (Ref 35, 38, 39), which illustrates significant improvements to the strength/ductility combination possible in materials processed via such techniques. Early work focused on conventional structural materials such as steels and various aluminum alloys, while highly alloyed and higher-strength materials such as maraging steels and nickel-base superalloys were similarly processed at temperatures as low as room temperature. The

Table 1 Summary of hydrostatic extrusion data for various materials without back pressure

Material	Die angle, degrees	Hardness, HV	
		Billet(a)	Product(b)
Iron and steel			
Armco iron (Ref 31, 67)	45	76	. . .
	90	76	. . .
Mild steel (Ref 31, 67)	45	113	195–277
Steel (0.15C) (Ref 59–62, 70)	45	. . .	. . .
AISI 1020 steel (Ref 69)	20	110	285
	90	. . .	. . .
Zn 58 (Ref 31, 67)	45	135	250–320
Zn 8 (Ref 31, 67)	45	148	240–280
D-2 steel (Ref 31, 67)	45	243	313
	45	243	370
AISI 4340 steel (Ref 33)	45	195	285–301
	45	195	301–393
High-speed steel (Ref 31, 67)	45	260	390–420
Rex 448 (Ref 31, 67)	45	340	370
High tensile (Ref 31, 67)	45	374	390–470
Cast iron (Ref 68)	45	198	191–249
316 stainless steel	20	. . .	490
High-temperature and refractory metals and alloys			
Beryllium (Ref 59–62, 70)	45	. . .	. . .
Beryllium (Ref 33)	45	. . .	. . .
Beryllium (hot extrusion) (Ref 69)	90	. . .	. . .
Chromium (Ref 78)	45	174	. . .
Molybdenum:			
Rolled (Ref 31, 67)	45	191	215–263
Sintered (Ref 31, 67)	45	216	252–298
Arc-cast (Ref 67)	45	242	263–308
Niobium (Ref 31, 67)	45	112	176–181
Niobium (Ref 33)	20	. . .	. . .
Nb-2%Zr (Ref 68)	45	281	. . .
Tantalum (Ref 31, 67)	45	78–120	127–183
Titanium (Ref 31, 67)	45	254	262–342
	45	310	299–324
Titanium (Ref 76)	20	. . .	. . .
Ti-6Al-4 V (Ref 76)	45	305	. . .
Tungsten (Ref 31, 67)	45	440	450–480
Vanadium (Ref 31, 67)	45	270	. . .
Zirconium (Ref 31, 67)	45	169	190
	30	170	. . .
Zircaloy (Ref 31, 67)	45	292	. . .
	90	265	. . .
Magnesium alloys			
Magnesium (Ref 31, 67)	45	28	. . .
Mg-1Al (Ref 31, 67)	45	36	. . .
	90	36	. . .
M/ZTY (Ref 31, 67)	45	57	76–92
ZW3 (Cast) (Ref 31, 67)	45	66	66–85
AZ91 (Cast) (Ref 31, 67)	45	93	102–116
Mg-Li (Ref 51, 52)	20	. . .	. . .
AZ91-SiC$_p$ (Ref 51, 52)	20	. . .	. . .
Aluminum alloys			
99.5% Al (Ref 31, 67)	45	24	43–50
	90	24	43–50
99.5% Al (Ref 33)	20	22	60
HE 30 Al (HD44) (Ref 31, 67)	45	51	. . .
	90	51	. . .
Al-11Si (Ref 31, 67)	45	62	80–93
Duralumin II (Ref 31, 67)	45	71	. . .
A/FLS (Ref 31, 67)	45	71	111
AD.1 (99.5 Al) (Ref 59–62, 70)	45	. . .	. . .
	80	. . .	. . .
Alloy A (2–2.8 Mg) (Ref 59–62, 70)	45	. . .	. . .
Alloy Ak6 (Ref 59–62, 70)	45	. . .	. . .
1100Al-O (Ref 33)	45	. . .	. . .
Al (annealed) (Ref 69)	90	. . .	. . .
Copper alloys			
ERCH (Ref 31, 67)	45	43	120
	90	43	. . .
M2 (99.7) (Ref 59–62, 70)	45	. . .	. . .
	80	. . .	. . .

(continued)

(a) Prior to hydrostatic extrusion. (b) After hydrostatic extrusion. (c) Mechanical properties (tension, compression) measured in references listed

Material	Die angle, degrees	Hardness, HV	
		Billet(a)	Product(b)
Copper alloys (continued)			
Copper (annealed) (Ref 33)	90	. . .	. . .
Copper (Ref 33)	20	. . .	. . .
60/40 Brass (Ref 31, 67)	45	127	181–184
60/40 Brass (L62) (Ref 59–62, 70)	80	. . .	. . .
Miscellaneous			
Bismuth (Ref 31, 67)	45	8	4
Yttrium (annealed) (Ref 33)	90	. . .	. . .
Zinc (Ref 33)	20	. . .	. . .
NiAl:			
Extruded at 25 °C (Ref 54, 56)(c)	20	225	725
	20	225	370–400
X2080Al-SiCp (Ref 28, 75)(c)	20	. . .	. . .

(a) Prior to hydrostatic extrusion. (b) After hydrostatic extrusion. (c) Mechanical properties (tension, compression) measured in references listed

beneficial stress state imparted by hydrostatic extrusion enabled large reductions at temperatures well below those possible with conventional extrusion where billets often exhibit extensive fracturing. The benefits of such low-temperature deformation processing was often carried out well below the recrystallization temperature of the material. It has often been demonstrated that the properties of hydrostatically extruded materials exhibited a better combination of properties (e.g., strength, ductility) than materials given an equivalent reduction via conventional extrusion (Ref 18, 28, 29, 32, 34, 35–38, 40–42, 73, 74).

The work outlined above on conventional structural materials revealed the potential benefits of hydrostatic extrusion. Many of the original materials studied already possessed sufficient ductility to enable processing with more conventional deformation-processing techniques, while additional property improvements provided through hydrostatic extrusion could be achieved by other means. However, the knowledge gained from studies on hydrostatic extrusion of conventional materials was utilized in the optimization of conventional extrusion die designs and lubricants that could impart such beneficial stress states in conventional forming processes.

Hydrostatic Extrusion of Composite Systems

The increased emphasis placed on the need for high-performance materials having high specific strength and stiffness in addition to improved high-temperature performance has promoted and renewed research and development efforts on a variety of composites as well as intermetallics. These materials typically possess lower ductility and fracture toughness than the conventional monolithic structural materials, both of which affect the deformation-processing characteristics. Composite systems may combine metals with other metals or ceramics that have large differences in flow stress, necking strain, work-hardening characteristics, ductility, and formability. In such cases, it is important to minimize (or heal) any damage that might evolve at or near the reinforcing phase during processing. Although intermetallics can be either single-phase or multiphase materials, the nature of atomic bonding in such systems may be significantly different compared with monolithic metals, resulting in materials having high stiffness and strength but reduced ductility, formability, and toughness. In such materials, it may be particularly important to investigate and understand the effects of changes in stress state on ductility or formability. In particular, hydrostatic extrusion experiments can provide important information regarding the processing conditions required for successful deformation processing while additionally enabling an evaluation of the properties of the extrudate.

In composite systems combining metals with different flow strength, ductility, and necking strains, hydrostatic extrusion has been shown to facilitate codeformation without fracture or instability in systems such as composite conductors (Ref 29, 36) and Cu-W (Ref 53), while powdered metals (Ref 80) have also been consolidated using such techniques. A limited number of investigations have been conducted on discontinuously reinforced composites (Ref 18, 28, 37), where there is potential interest in cold extrusion (Ref 41–43) of such systems. A potential problem in such systems during deformation processing relates to damage to the reinforcement materials as well as fracture of the billet because of the limited ductility of the material, particularly at room temperature.

The potential advantages of low-temperature processing include the ability to significantly strengthen the composite and inhibit the formation of any reaction products at the particle/matrix interfaces since deformation processing is conducted at temperatures lower than that where significant diffusion, recovery, and recrystallization occur. Preliminary work on such systems (Ref 18, 28, 37) revealed that the strength increment obtained after hydrostatic extrusion of the composites was greater than that obtained in the monolithic matrix processed to the same reduction. In addition, hydrostatic extrusion into a back pressure inhibited billet cracking in a number of cases (Ref 75), consistent with similar observations in monolithic metals (Ref 34). Separate studies (Ref 18, 28, 75) also revealed an effect of reinforcement size on both the hydrostatic pressure required for extrusion (Fig. 8) as well as the amount of damage to the reinforcement at various positions in the extrudate as shown in Fig. 9.

Table 2 compares the experimentally obtained extrusion pressures (Ref 18, 28, 75) with those predicted by the models of Pugh (Ref 31) and Avitzur (Ref 30, 33) reviewed previously, assuming different values for the coefficient of friction μ. It appears that the initial high level of work hardening in such composites (Ref 18, 28, 75, 82) provides a considerable divergence from the values for extrusion pressure predicted by the models based on non-work-hardening materials, while monolithic X2080Al, which exhibits lower

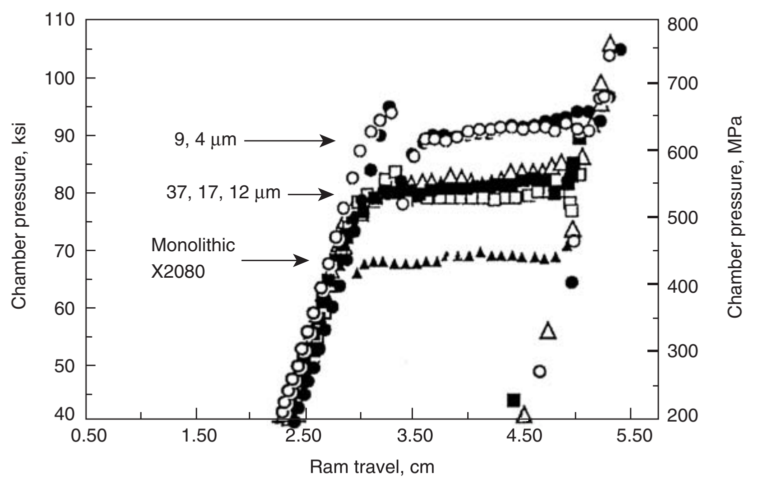

Fig. 8 Effect of reinforcement size on extrusion pressure versus ram travel discontinuously reinforced aluminum. Source: Ref 28, 75

work hardening, extrudes at pressures more closely estimated by the models for a non-work-hardening material. Clearly, more work is needed over a wider range of conditions, for example, matrix alloys, reinforcement sizes, shapes, and volume (fraction), in order to support the generality of such observations. Damage to the reinforcement was shown to affect modulus, strength, and ductility of the extrudate in those studies (Ref 18, 28, 75) while superimposition of hydrostatic pressure facilitated deformation.

Hydrostatic Extrusion of Brittle Materials

Most brittle materials are subject to circumferential (transverse) and longitudinal surface cracking during hydrostatic extrusion. This cracking can be avoided through the use of either fluid-to-fluid extrusion or double-reduction dies. In fluid-to-fluid extrusion, the billet is hydrostatically extruded into a fluid at a lower pressure. Disadvantages include high tooling and operating costs, while extrusion lengths are limited to the length of the secondary chamber. Increased fluid pressure is also required for fluid-to-fluid extrusion, limiting its usefulness for most industrial applications.

Research at Battelle Columbus Division (Ref 83) led to the development of the double-reduction die in order to address the problem of extruding low-ductility metals. Earlier work (Ref 84) had established that cracks or fracture in rod and tube drawing first developed in the section immediately before the exit plane of the die, with surface cracking arising from residual tensile stresses as the product left the die. Longitudinal or transverse cracks were observed across the extruded product, depending on whether the predominant residual stresses were longitudinal or circumferential. However, residual stresses at the surface could be reversed to compressive stresses by a subsequent draw with a low reduction in area (<2%). The double-reduction die was designed to provide a 2% reduction in the second step. The small second reduction apparently inhibits cracking by imposing an annular counterpressure on the extrusion as it exits the first portion of the die, thereby counteracting axial tensile stresses arising from residual stresses, elastic bending, and friction. Elimination of circumferential cracks after exit from the second portion of the die was attributed to the favorable permanent change in residual stresses in the workpiece produced by the small second reduction (Ref 85). This method has been successfully applied to the extrusion of some brittle and semibrittle materials, including beryllium and TZM molybdenum (titanium, zirconium, molybdenum) alloy, using polytetrafluoroethylene (PTFE) as the lubricant, and castor oil as the pressurizing fluid. This approach may be applicable to conventional cold extrusion through a lubricated conical die (Ref 83).

Hydrostatic Extrusion of Intermetallics or Intermetallic Compounds

Comparatively fewer studies have been conducted to determine the effects of superimposed pressure on the formability of intermetallics or materials based on intermetallic compounds. Recent efforts conducted on both NiAl and TiAl (Ref 54, 56, 76, 86, 87) have revealed significant effects of superimposed pressure on both formability and mechanical properties of the hydrostatically extruded billet. Polycrystalline NiAl typically exhibits low ductility (e.g., fracture strain <5%) and fracture toughness (e.g., <5 MPa $\sqrt{m}$, or 4.6 ksi $\sqrt{in.}$) at room temperature, with a ductile-to-brittle transition temperature (DBTT) of ~300 °C (570 °F) (Ref 88, 89). The observation of significant pressure-induced ductility increase (Ref 54–56, 90–94) combined with a beneficial change in fracture mechanism from intergranular + cleavage to intergranular + quasi-cleavage suggests that hydrostatic extrusion can be utilized to deformation process such material at temperatures near the DBTT. Although hydrostatic extrusion (with backpressure) of NiAl at 25 °C (77 °F) exhibited excessive billet cracking, similar extrusion conditions conducted on NiAl at 300 °C (570 °F) were successful (Ref 54). The ability to hydrostatically extrude NiAl at such low temperatures enabled the retention of a beneficial dislocation substructure and a change in texture of the starting material (Ref 54, 55, 93). Both strength (hardness) and toughness were increased in the extrudate (Ref 54). The strength was increased from 200 to 400 MPa (30 to 60 ksi) while toughness increased from 5 to ~12 MPa $\sqrt{m}$ (4.6 to 10.9 ksi $\sqrt{in.}$). In addition, *R* curve behavior was exhibited by the hydrostatically extruded NiAl, with a peak toughness of ~28 MPa $\sqrt{m}$ (25.5 ksi $\sqrt{in.}$), as summarized in Fig. 10. Such changes in strength and toughness were accompanied by a complete change in fracture mechanism of NiAl (Ref 54). Preliminary experiments on TiAl (Ref 76, 87), hot worked with superimposed pressure at higher temperatures, have also shown that pressure inhibits cracking in the deformation-processed material, though the resulting properties were not measured in these studies.

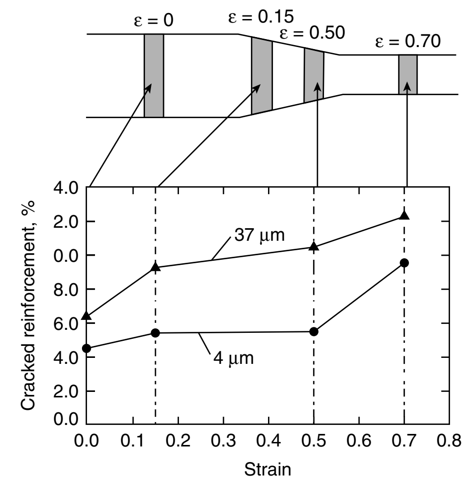

Fig. 9 Effect of reinforcement size and strain on damage to reinforcement in hydrostatically extruded billet. Source: Ref 28, 75

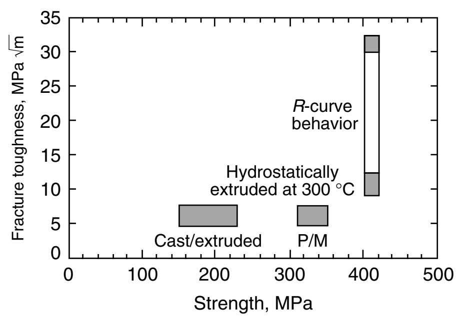

Fig. 10 Fracture toughness-strength combinations for NiAl processed via different means. P/M, powder metallurgy. Source: Ref 54

Table 2 Comparison of hydrostatic extrusion pressures obtained for monolithic 2080 and 2080 composites containing different size SiC_p to model predictions

		Predicted extrusion pressure, MPa					
		Pugh, Eq 1(a), work-hardening		Pugh, Eq 4(b), non-work-hardening		Avitzur, Eq 5(b), non-work-hardening	
Material	Extrusion pressure, MPa	μ = 0.2	μ = 0.3	μ = 0.2	μ = 0.3	μ = 0.2	μ = 0.3
Monolithic X2080	476	654	771	557	663	559	656
X2080-15SiC_p (SiC_p size):							
4 μm	648–662	698	824	608	724	611	717
9 μm	648–676	695	820	607	723	610	715
12 μm	572	661	780	579	689	581	682
17 μm	552–559	653	771	579	689	581	682
37 μm	552–579	615	725	558	665	561	658

Hydrostatic extrusion pressures obtained: Ref 28, 75; models: Ref 1, 30, 59, 81. (a) $\sigma = (\sigma_{0.1\%y} + UTS)/2$. (b) $\sigma = \sigma_y$

Hot Hydrostatic Extrusion

In addition to cold hydrostatic extrusion, attempts have been made to extrude conventional metals at elevated temperatures, as reviewed above for intermetallics. This has been shown (Ref 95) to be beneficial for difficult-to-work materials such as high-strength aluminum alloys, titanium alloys, refractory metals and alloys, bimetallic products, and multifilament superconductors. The hot process has also been used for the production of copper tubing at extrusion ratios on the order of 500 to 1. One of the main issues regarding hot hydrostatic extrusion relates to identifying pressure media that can withstand elevated temperatures. The pressure media used in cold or warm processes (e.g., castor oil or other vegetable oils) ignite and burn at high temperatures.

The use of a viscoplastic pressure medium for hot hydrostatic extrusion (Ref 95) provides an alternative as these materials are soft solids at room temperature. This enables the pressure medium to be introduced into the container without the need for a charging pump, thereby simplifying machine design. Viscoplastic pressure media used for hot hydrostatic extrusion include a variety of waxes, such as beeswax, carnauba wax, mountain wax, lanolin, and complex waxes. In addition, soap-type greases composed of petroleum oil and such soaps as fatty acids or soaps of sodium, calcium, or lithium have been utilized. High-molecular-weight polymers, such as polyethylene can be used, while properties of these materials depend on their molecular weight and the additives used. Finally, mixtures of nonsoap greases and silica or other metal oxides provide high-temperature possibilities, while mixtures of petroleum oil and bentonite are heat resistant up to 1200 °C (2190 °F). While other metal oxides, salts, and glass can be used as pressure media for hot hydrostatic extrusion, these materials may adhere to the extruded product and can be difficult to remove.

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