### TABLE 18-6 Comparison of Four Powder Processing Methods

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Conventional Press and Sinter</th>
<th>Metal Injection Molding (MIM)</th>
<th>Hot-Isostatic Pressing (HIP)</th>
<th>P/M Forging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of workpiece</td>
<td>Intermediate</td>
<td>Smallest</td>
<td>Largest</td>
<td>Intermediate</td>
</tr>
<tr>
<td></td>
<td>&lt;5 pounds</td>
<td>&lt;1/4 pounds</td>
<td>1-1000 pounds</td>
<td>&lt;5 pounds</td>
</tr>
<tr>
<td>Shape complexity</td>
<td>Good</td>
<td>Excellent</td>
<td>Very good</td>
<td>Good</td>
</tr>
<tr>
<td>Production rate</td>
<td>Excellent</td>
<td>Good</td>
<td>Poor</td>
<td>Excellent</td>
</tr>
<tr>
<td>Production quantity</td>
<td>&gt;5000</td>
<td>&gt;5000</td>
<td>1-1000</td>
<td>&gt;10,000</td>
</tr>
<tr>
<td>Dimensional precision</td>
<td>Excellent</td>
<td>Good</td>
<td>Poor</td>
<td>Very good</td>
</tr>
<tr>
<td></td>
<td>±0.001 in./in.</td>
<td>±0.003 in./in.</td>
<td>±0.020 in./in.</td>
<td>±0.0015 in./in.</td>
</tr>
<tr>
<td>Density</td>
<td>Fair</td>
<td>Very good</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Mechanical properties</td>
<td>80-90% of wrought</td>
<td>90-95% of wrought</td>
<td>Greater than wrought</td>
<td>Equal to</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>Intermediate</td>
<td>High</td>
<td>Somewhat low</td>
</tr>
<tr>
<td></td>
<td>$0.50-5.00/lb</td>
<td>$1.00-10.00/lb</td>
<td>&gt;$100.00/lb</td>
<td>$1.00-5.00/lb</td>
</tr>
</tbody>
</table>

### Key Words
- amorphous
- apparent density
- atomization
- binder
- blending
- burn-off
- canning
- coining
- compaction
- composites
- compressibility
- compaction
- flow rate
- gas atomization
- green strength
- hot-isostatic pressing (HIP)
- impregnation
- infiltration
- isostatic compaction
- liquid-phase sintering
- lubricant
- metal injection molding (MIM)
- mixing
- particle shape
- particle size
- permeability
- P/M forging
- porosity
- powder injection molding (PIM)
- powder metallurgy
- prealloyed powder
- pressure-assisted sintering
- protective atmosphere
- rapidly solidified powder
- repressing
- secondary operations
- sinter-HIP
- sintering
- size distribution
- sizing
- spray forming (Osprey process)
- surface texture
- vacuum sintering
- warm compaction
- water atomization

### Review Questions

1. What type of product would be considered to be a prospect for powder metallurgy manufacture?
2. What were some of the earliest powder metallurgy products?
3. What are some of the primary market areas for P/M products?
4. Which metal family currently dominates the powder metallurgy market?
5. What are the four basic steps that are usually involved in making products by powder metallurgy?
6. What are some of the important properties and characteristics of metal powders to be used in powder metallurgy?
7. What is the most common method of producing metal powders?
8. What are some of the other techniques that can be employed to produce particulate material?
9. Which of the powder manufacturing processes are likely to be restricted to the production of elemental (unalloyed) metal particles?
10. What are some of the unique properties of amorphous metals?
11. Why is powder metallurgy a key process in producing products from amorphous or rapidly solidified material?
12. Why is flow rate an important powder characterization property?
13. What is apparent density, and how is it related to the final density of a P/M product?
14. What is green strength, and why is it important to the manufacture of high-quality P/M products?
15. How do the various powder properties relate to the method of powder manufacture?
16. What are some of the objectives of powder mixing or blending?
17. How does the addition of a lubricant affect compressibility? Green strength?
18. How might the use of a graphite lubricant be fundamentally different from the use of wax or stearates?
19. What types of composite materials can be produced through powder metallurgy?
20. What are some of the objectives of the compaction operation?
21. What limits the cross-sectional area of most P/M parts to several square inches or less?
22. Describe the movement of powder particles during compaction. What feature is responsible for the fact that powder does not flow and transmit pressure like a liquid?
23. For what conditions might a double-action pressing be more attractive than compaction with a single moving punch?
24. How is the density of a P/M product typically reported?
25. Why is it more difficult to compact a multiple-thickness part?
26. Describe the four classes of conventional powder metallurgy products.
27. What is isostatic compaction? For what product shapes might it be preferred?
28. What is the benefit of warm compaction?
29. What is a reasonable compacted density? How much residual porosity is still present?
30. What types of materials are used in compaction tooling?
31. How do the common sintering temperatures compare to material melting points?
32. What are the three stages associated with most P/M sintering operations?
33. Why is it necessary to raise the temperature of P/M compacts slowly to the temperature of sintering?
34. Why is a protective atmosphere required during sintering? During the cool-down period?
35. What types of atmospheres are used during sintering?
36. What are some of the changes that occur to the compact during sintering?
37. What is the purpose of the sinter brazing process?
38. The combined heating and pressing of powder would seem to be an improvement over separate operations. What features act as deterrents to this approach?
39. What are some of the attractive properties of hot-isostatic pressed products?
40. What is the attractive feature of the sinter-HIP and pressure-assisted sintering processes?
41. What are some of the other methods that can produce high-density P/M products?
42. Describe the spray-forming process and the unique feature that enables production of high-density, fine grain size products.
43. How is the injection molding of powdered material similar to the injection molding of plastic or polymeric products?
44. In the MIM process, what is done to enable metal powder to flow like a fluid under pressure?
45. How is the metal powder used in metal injection molding (MIM) different from the metal powder used in a conventional press-and-sinter production?
46. What are some of the ways that the binder can be removed from metal injection molded parts?
47. Why are MIM products injection molded to sizes that are considerably larger than the desired product?
48. For what types of parts is P/M injection molding an attractive manufacturing process?
49. How does the final density of a MIM product compare to a press-and-sinter P/M part?
50. What is the purpose of repressing, coining, or sizing operations?
51. Why can't we use the original compaction tooling to perform repressing?
52. What is the major difference between repressing and P/M forging?
53. What is the difference between impregnation and infiltration? How are they similar?
54. Why might different conditions be required for the heat treatment, machining, or surface treatment of a powder metallurgy product?
55. The properties of P/M products are strongly tied to density. Which properties show the strongest dependence?
56. How do the physical properties of P/M products vary with density?
57. What advice would you want to give to a person who is planning to convert the manufacture of a component from die casting to powder metallurgy?
58. What is the shape of an “ideal” powder metallurgy product?
59. What are some P/M products that have been intentionally designed to use the porosity or permeability features of the process?
60. Give an example of a product where two or more materials are mixed to produce a composite P/M product with a unique set of properties.
61. What are the most cited assets of the powder metallurgy method of parts manufacture?
62. Why is finish machining such an expensive component in parts manufacture?
63. Describe some of the materials that can be made into P/M parts that could not be used for processes such as casting and forming.
64. Why is P/M not attractive for parts with low production quantities?
65. What features of the P/M process often compensate for the higher cost of the starting material?
66. How might you respond to the criticism that P/M parts have inferior properties?

**Problems**

1. When specifying the starting material for casting processes, the primary variables are chemistry and purity. Any structural features of the starting material will be erased by the melting. For forming processes, the material remains in the solid state, so the principal concerns relating to the starting material are chemistry and purity, ductility, yield strength, strain-hardening characteristics, grain size, and so on. What are some of the characteristics that should be specified for the starting powder to assure the success of a powder metallurgy process? In what ways are these similar to or different from those mentioned for casting and forming processes?
2. In conventional powder metallurgy manufacture, the material is compacted with applied pressure at room temperature and then sintered by elevated temperature at atmospheric pressure. With P/M hot pressing, the loose powder is subjected to pressure while it is also at elevated temperature. It would appear, therefore, that hot pressing could produce a finished part in a single operation and would be a more economical and attractive manufacturing process. What features have been overlooked in this argument that would tend to favor the press-and-sinter sequence for conventional manufacture?
3. Investigate the method(s) used to produce tungsten incandescent lamp filaments. How does the method used today compare to the method developed by Coolidge in the late 1800s?