This invention relates to an improved method of rolling magnesium-base alloys, having sufficient ductility to permit substantial deformation, i.e., those metals usually containing more than 50 per cent of magnesium, together with a minor proportion of one or more alloying elements such as aluminum, manganese, zinc, calcium, cadmium, cerium, silver, and silicon.

Hereinafter, plates and sheets of magnesium-base alloys have been fabricated principally by rolling the metal to size at a temperature at or above its recrystallization temperature, which for most alloys is well above 400° F., usually above 500° F., and then annealing it. In a variation of this procedure, the metal, after hot rolling nearly to final size at a temperature above 400° F., is given a relatively small cumulative reduction in thickness at a temperature below 350° F. These methods, while resulting in rolled articles useful for many purposes, are not successful in developing products having both strength and elongation characteristics which approach the maximum obtainable for the particular alloy being worked.

We have now found, however, that it is possible to prepare rolled magnesium alloy articles having both high strength and high elongation by subjecting the metal during fabrication to a relatively great reduction in thickness while at a temperature below the recrystallization temperature of the metal, i.e., below about 500° F. The process of the invention, then, essentially comprises forming an intermediate product having a thickness at least 25 per cent above the final thickness desired for the finished article, rolling the said product down to final thickness while at a temperature below its recrystallization temperature, and then annealing the rolled product.

In practice, the intermediate product is ordinarily formed at a temperature above 400° or 500° F. to a thickness of between 25 and about 500 per cent above the desired final thickness, values above 60 per cent being distinctly preferred. This forming operation may be carried out in any desired way, as by extrusion, or more commonly by conventional rolling procedure. In the latter case, the magnesium-base alloy is cast or extruded into a rolling slab, and the slab is passed repeatedly between the rolls of a mill while at a constant or continuously decreasing temperature within the range between about 500° F. and about 400° F., until the desired intermediate thickness is attained. The metal is then annealed, usually at a temperature of 500° F. to 900° F., for 0.5 to 2 hours or more. If the preliminary rolling is carried out entirely above 600° F., or sometimes even 500° F., annealing is not required.

The intermediate product formed as described is then rolled to approximately final thickness while at a constant or continuously decreasing temperature below its recrystallization temperature, e.g., below about 500° F. for most magnesium-base alloys. Rolling temperatures at or below 400° F., are preferred, ordinary room temperature being convenient in most instances. The rolling to final thickness is ordinarily effected by passing the metal repeatedly between rolls adjusted to cause a 0.1 to 20 per cent reduction in thickness per pass, although higher reductions are sometimes possible. In general it is preferable to effect the total reduction to approximately final thickness in the minimum number of passes which the metal will stand without fracture.

After the final rolling to finished thickness, the metal is ordinarily annealed, e.g., at a temperature of 300° to 800° F. for 0.1 to 2.0 hours.

The process of the invention is applicable to making magnesium alloy articles of any desired thickness, but is particularly advantageous in making relatively thin rolled sheets.

The following examples will illustrate the invention, but are not to be construed as limiting its scope:

**Example 1**

A magnesium-base alloy containing 2.0 per cent manganese and 0.15 per cent calcium, the balance being magnesium, was cast into an ingot and then extruded to form a rolling slab. The slab was then heated to a temperature of 800° F. and repeatedly passed between rolls while at said temperature until the thickness of the metal was 0.100 inch, after which the sheet so produced was annealed at 500° F. for 30 minutes. The annealed sheet was then rolled at a substantially constant temperature of 400° F. at a reduction of 5 per cent per pass until the thickness was 0.060 inch, after which the rolled sheet was annealed at 600° F. for 0.5 hour. The annealed sheet exhibited the following properties in the direction of rolling: elongation, 17.5 per cent in 2 inches; yield strength, 19,700 pounds per square inch; tensile strength, 35,200 pounds per square inch.

When the foregoing process was repeated exactly except that the reduction per pass in the final rolling step was 10 per cent, and the final annealing was at 500° F., the properties of the annealed sheet were: elongation, 19.5 per cent, yield strength, 20,800 pounds per square inch; tensile strength, 34,200 pounds per square inch.
Example 2
The process of Example 1 using a 5 per cent reduction per pass was repeated exactly, except that the intermediate anneal at 900° F. was omitted, and the final anneal was at 800° F. The properties of the resulting sheet were: elongation, 18.5 per cent; yield strength, 25,100 pounds per square inch; tensile strength, 36,000 pounds per square inch.

Example 3
The process of Example 2 was repeated except that the final rolling operation was carried out at 300° F., and the final anneal was at 700° F. The properties of the resulting sheet were: elongation, 19.5 per cent; yield strength, 24,100 pounds per square inch; tensile strength, 35,100 pounds per square inch.

Example 4
A magnesium-base alloy containing 2.0 per cent manganese and 0.15 per cent cerium, the balance being magnesium, was cast into a billet and extruded into a rolling slab. The slab was then heated to a temperature of 800° F. and rolled at that temperature until a thickness of 0.100 inch resulted, after which the resulting product was annealed at 800° F. for 30 minutes. The annealed sheet was then rolled at a temperature of 460° F. at a reduction of 20 per cent per pass until the thickness was 0.060 inch, after which the sheet was annealed at 700° F. for 0.5 hour. The properties of the annealed sheet in the direction of rolling were: elongation, 18.0 per cent in 2 inches; yield strength, 21,400 pounds per square inch, tensile strength, 36,600 pounds per square inch.
When the foregoing process was repeated except that the final rolling at 400° F. was carried out until the sheet was 0.040 inch thick, the properties of the final annealed sheet were: elongation, 18.0 per cent; yield strength, 22,900 pounds per square inch; tensile strength, 37,300 pounds per square inch.

Example 5
A magnesium-base alloy containing 6.0 per cent aluminum, 0.7 per cent zinc, and 0.3 per cent manganese, the balance being magnesium, was cast into a billet and extruded into rolling bars. The individual bars were then rolled to the various intermediate thicknesses stated in the following table at a temperature of 700° F., the rolls being adjusted to give a reduction of about 25 per cent per pass. The resulting rolled strips were then further rolled to a final thickness of 0.060 inch at the temperature and reduction per pass indicated in the table, after which they were annealed at a temperature of 500° F. for 0.5 hour. The properties of the resulting strips are given in the table.

<table>
<thead>
<tr>
<th>Table</th>
<th>Final rolling temp.</th>
<th>Intermediate thickness</th>
<th>Reduction per pass</th>
<th>Elongation in 2 inches</th>
<th>Yield strength</th>
<th>Tensile strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>°F.</td>
<td>Inches</td>
<td>Per cent</td>
<td>Per cent</td>
<td>Lbs./sq. in.</td>
<td>Lbs./sq. in.</td>
<td>Lbs./sq. in.</td>
</tr>
<tr>
<td>200</td>
<td>0.060</td>
<td>5</td>
<td>21.2</td>
<td>28,700</td>
<td>44,400</td>
<td>44,400</td>
</tr>
<tr>
<td>400</td>
<td>0.080</td>
<td>5</td>
<td>18.7</td>
<td>30,900</td>
<td>44,800</td>
<td>44,800</td>
</tr>
<tr>
<td>600</td>
<td>0.100</td>
<td>4</td>
<td>21.0</td>
<td>33,000</td>
<td>46,700</td>
<td>46,700</td>
</tr>
<tr>
<td>800</td>
<td>0.120</td>
<td>4</td>
<td>19.0</td>
<td>33,600</td>
<td>46,800</td>
<td>46,800</td>
</tr>
</tbody>
</table>

Example 6
A magnesium-base alloy containing 1.6 per cent manganese and 0.15 per cent calcium, the balance being magnesium, was cast into a billet and extruded into a rolling slab. The slab was then rolled at a temperature of 750° F. to 500° F. to a thickness of 0.072 inch. The resulting sheet was then cooled to room temperature (75° F.) and rolled to a final thickness of 0.021 inch at a reduction of 0.1 to 1.0 per cent per pass, after which it was annealed at 575° F. for one hour. The properties of the resulting sheet in the direction of rolling were: elongation, 18.1 per cent in 2 inches; yield strength, 28,300 pounds per square inch; ultimate strength, 37,100 pounds per square inch.
When the foregoing process was repeated except that the final cold rolling was preceded by an annealing operation at 750° F. for one hour, the properties of the final sheet were: elongation, 19.4 per cent; yield strength, 27,000 pounds per square inch; ultimate strength, 36,800 pounds per square inch.

Example 7
A magnesium-base alloy rolling slab prepared as in Example 6 was rolled at a continuously decreasing temperature in the range 800°-500° F. until a thickness of 0.165 inch was reached, after which the sheet was annealed at 700° F. for 0.5 hour. Rolling was then continued at decreasing temperatures in the range 500°-75° F. until a final thickness of 0.064 inch was attained, when the sheet was annealed at a temperature of 500° F. for 0.3 hour. The properties of the sheet were: elongation 22.0 per cent in 2 inches; yield strength, 26,900 pounds per square inch, tensile strength, 35,200 pounds per square inch.

Example 8
A magnesium-base alloy rolling slab, prepared as in Example 6, was rolled at a decreasing temperature in the range 800°-500° F. until a thickness of 0.040 inch was reached, after which the sheet was annealed at 700° F. for 0.5 hour. The sheet was allowed to cool to 80° F. and was then rolled in 20 passes to a thickness of 0.020 inch, during which time the temperature of the sheet did not exceed 85° F. The metal was then annealed for 0.5 hour at 600° F. The properties of the sheet were: elongation, 17.2 per cent; yield strength, 26,500 pounds per square inch; tensile strength, 35,500 pounds per square inch.

Example 9
A magnesium-base alloy slab, prepared as in Example 6, was rolled at temperatures in the range 800°-500° F. until a thickness of 0.072 inch was reached, after which the slab was annealed at 700° F. for 0.5 hour. The metal was then repeatedly rolled at a decreasing temperature in the range 350°-75° F. until the thickness was 0.015 inch. The sheet was then annealed for 1.0 hour at 470° F. The properties of the sheet were: elongation, 19.0 per cent; yield strength, 29,800 pounds per square inch; tensile strength, 37,500 pounds per square inch.

Example 10
A magnesium-base alloy containing 4.0 per cent aluminum, and 0.3 per cent manganese was cast into a billet and extruded into a tube of 700°-800° F. into a tube having a wall thickness of 0.322 inch. The tube was slit longitu-
nally and flattened into a plate, and then annealed at 800° F. for 1.0 hour. This plate was then repeatedly rolled at about room temperature until a thickness of 0.258 inch was reached, after which it was annealed at 700° F. for 1.0 hour. The properties of the rolled sheet were: elongation, 16.5 per cent; yield strength, 13,500 pounds per square inch; tensile strength, 35,900 pounds per square inch.

While the previous examples illustrate a variety of rolling procedures, in all of them the metal is first formed to a thickness between about 25 and about 500 per cent above the desired final thickness, and is then rolled to final thickness while at a temperature well below the recrystallization temperature of the metal, usually at 400° F. or lower. The heavy cold rolling results in products having a combination of higher strength and higher elongation than have heretofore been attained with magnesium alloys, the improvements in yield strength being especially marked.

The foregoing description is illustrative rather than strictly limiting, the invention being co-extensive in scope with the following claims.

We claim:
1. In a method of producing a high strength ductile product from a magnesium-base alloy having sufficient ductility to permit substantial deformation, the steps which comprise forming a product having a thickness of at least 25 per cent above the desired final thickness, rolling the product to approximately final thickness while at a temperature below the recrystallization temperature of the metal and below 400° F., and then annealing the rolled product.
2. In a method of producing a high strength ductile rolled sheet from a magnesium-base alloy having sufficient ductility to permit substantial deformation, the steps which comprise forming a sheet having a thickness of between about 60 and about 500 per cent above the desired final thickness, rolling the said sheet to approximately final thickness while at a temperature below the recrystallization temperature of the metal and below 400° F., and then annealing the rolled sheet.
3. In a method of producing a high strength ductile rolled product from a magnesium-base alloy having sufficient ductility to permit substantial deformation, the steps which comprise rolling the metal to a thickness of between about 60 and about 500 per cent above the desired final thickness while at a temperature between about 800° F. and about 400° F. then rolling the metal to approximately final thickness while at a temperature below the recrystallization temperature of the metal and below 400° F., and annealing the rolled sheet.
4. In a method of producing a high strength ductile rolled product from a magnesium-base alloy having sufficient ductility to permit substantial deformation, the steps which comprise rolling the metal to a thickness of between about 60 and about 500 per cent above the desired final thickness while at a temperature between about 800° F. and about 400° F., and then annealing the resulting product at a temperature between 500° F. and 800° F., rolling the annealed metal down to approximately final thickness while at a temperature below its recrystallization temperature, said rolling temperature being below 500° F., and annealing the rolled metal at a temperature between 300° F. and 500° F.
5. In a method of producing a high strength ductile rolled product from a magnesium-base alloy having sufficient ductility to permit substantial deformation, the steps which comprise rolling the metal to a thickness of between about 60 and about 500 per cent above the desired final thickness at a continuously decreasing temperature above 500° F., then rolling down to approximately final thickness at a continuously decreasing temperature below the recrystallization temperature of the metal and below 500° F., and annealing the rolled product.
6. In a method of producing a high strength ductile rolled product from a magnesium-base alloy having sufficient ductility to permit substantial deformation, the improvement which comprises effecting the size reduction from a thickness of at least 25 per cent above the desired final thickness down to approximately final thickness by passing the product between rolls while at a temperature below the recrystallization temperature of the metal and below 400° F.
7. In a method of producing a high strength ductile rolled product from a magnesium-base alloy having sufficient ductility to permit substantial deformation, the steps which comprise effecting the size reduction from a thickness between 60 and 500 per cent above the desired final thickness down to approximately final thickness by passing the product between rolls while at a temperature below the recrystallization temperature of the metal and below 400° F., and then annealing the rolled product at a temperature between 300° F. and 800° F.
8. In a method of producing a high strength ductile rolled product from a magnesium-base alloy having sufficient ductility to permit substantial deformation which has previously been rolled to a thickness of from 25 to 500 per cent above the desired final thickness at a temperature above 600° F., the steps which comprise rolling the same to final thickness at a temperature below its recrystallization temperature, said rolling temperature being below 500° F., and annealing the rolled product.
9. In a method of producing a high strength ductile rolled product from a magnesium-base alloy having sufficient ductility to permit substantial deformation which has previously been rolled to a thickness of from 25 to 500 per cent above the desired final thickness at a temperature above 400° F., and then annealed, the steps which comprise rolling the same to final thickness at a temperature below the recrystallization temperature of the metal and below 400° F., and then annealing the rolled product.

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