Lecture 6

High-Strength Steels for Engineering Applications

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Applications
Processing

Hot-forged crankshaft

Crankshaft machining; full annealing or spheroidizing before machining makes the machining easier.
Processing and Required Properties

Processing:

- Generally require machining and thermal treatment before use
- Quenching to obtain non-diffusional phases primarily martensite and in some cases bainite
- Tempering to adjust the final properties

Main requirements:

- High hardness and strength
- High toughness
- High fatigue strength under dynamic loading

Cold formability is generally not a requirement.

Heat treatments to form martensite are generally applied to steels containing more than 0.3% C (weldability is not a requirement). In these steels, the gains in hardness are most substantial.
Hardenability

**Definition of hardenability:** the ability of a steel to form martensite on quenching

Steels with a low hardenability may become martensitic only in thin sections.
Hardenability

**AISI 1040:**
0.39%C, 0.72%Mn, 0.23%Si, 0.018%S, 0.010%P
\(\text{Ac}_1=728\, ^\circ\text{C}, \text{Ac}_3=786\, ^\circ\text{C}\)

**AISI 1541:**
0.39%C, 1.56%Mn, 0.21%Si, 0.024%S, 0.010%P
\(\text{Ac}_1=716\, ^\circ\text{C}, \text{Ac}_3=788\, ^\circ\text{C}\)

Hardenability

Hardness profile of bars with different diameters after water quenching

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Cr</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAE 1045</td>
<td>0.48</td>
<td>0.60</td>
<td>0.022</td>
<td>0.016</td>
<td>0.17</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>SAE 6140</td>
<td>0.42</td>
<td>0.73</td>
<td>0.027</td>
<td>0.023</td>
<td>0.25</td>
<td>0.94</td>
<td>0.17</td>
</tr>
</tbody>
</table>
Hardenability

Hardness profile in the radial direction of a round bar of 42CrMo4 in the water-quenched condition and after tempering as indicated.

As-quenched from 930 °C

10 min 500 °C

10 min 600 °C

10 min 670 °C
Hardenability

An almost binary Fe-1.4%C steel water quenched from 1150 °C (~4 mm thick)

Due to the extremely low hardenability, pearlite (dark phase) has formed at former austenite grain boundaries. The rest of the microstructure consists of martensite plates (colorful) and retained austenite (bright matrix phase).
Hardenability

Hardness profile of bars with different diameters after oil quenching

![Graph showing hardness profile for SAE 1045 and SAE 6140 steels with 1% Cr addition.]

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
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<td>0.023</td>
<td>0.25</td>
<td>0.94</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Jominy End-Quench Hardenability Test

Jominy end-quench test setup for hardenability determination

- Specimen
- Water spray

- Slow cooling
- Fast cooling

Specimen

Water spray
Jominy End-Quench Hardenability Test

Jominy end-quench specimen

Temperature, °C

Cooling time, sec

Hardness, HRC

Distance from quenched end, cm

M M + nodular pearlite Fine pearlite Pearlite

CCT TTT
Alloying Elements and Hardenability

Comparative influence of alloying elements on hardenability

AISI 4340
0.4%C, 0.8%Cr, 0.25%Mo, 1.8%Ni

AISI 4140
0.4%C, 1%Cr, 0.2%Mo

AISI 8640
0.4%C, 0.5%Cr, 0.2%Mo, 0.5Ni

AISI 4042
0.4%C, 0.25%Mo

AISI 1042
0.4%C

Toughness of Martensite

**Hardness**

<table>
<thead>
<tr>
<th>Martensite</th>
<th>HRC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>40</td>
</tr>
</tbody>
</table>

SAE 1340:

- 0.43C
- 0.24Si
- 1.79Mn
- 0.07Cr
- 0.11Ni
- 0.02Al
- 0.006N

Influence of alloying elements on the impact energy of martensitic steels tempered below 200 °C

**Steel Grade:**

<table>
<thead>
<tr>
<th>Steel Grade</th>
<th>% C</th>
<th>% Si</th>
<th>% Mn</th>
<th>% Cr</th>
<th>% Mo</th>
<th>% Ni</th>
<th>% Al</th>
<th>% N</th>
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<tbody>
<tr>
<td>SAE 1340</td>
<td>0.43</td>
<td>0.24</td>
<td>1.79</td>
<td>0.07</td>
<td>0</td>
<td>0.11</td>
<td>0.020</td>
<td>0.006</td>
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<tr>
<td>SAE 1355</td>
<td>0.56</td>
<td>0.29</td>
<td>1.82</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>SAE 4340</td>
<td>0.38</td>
<td>1.57</td>
<td>0.88</td>
<td>0.84</td>
<td>0.32</td>
<td>1.82</td>
<td>0.027</td>
<td>0.07</td>
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<tr>
<td>SAE 5145</td>
<td>0.45</td>
<td>0.17</td>
<td>0.68</td>
<td>0.95</td>
<td>0.02</td>
<td>0.04</td>
<td>0.024</td>
<td>0.001</td>
</tr>
</tbody>
</table>

(coarse-grained steel)
# Toughness of Q&T Steels

<table>
<thead>
<tr>
<th>Steel Grade</th>
<th>% C</th>
<th>% Si</th>
<th>% Mn</th>
<th>% Cr</th>
<th>% Mo</th>
<th>% Ni</th>
<th>% Al</th>
<th>% N</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAE 1340</td>
<td>0.43</td>
<td>0.24</td>
<td>1.79</td>
<td>0.07</td>
<td>0</td>
<td>0.11</td>
<td>0.020</td>
<td>0.006</td>
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<tr>
<td>SAE 2345</td>
<td>0.44</td>
<td>0.26</td>
<td>0.83</td>
<td>0.06</td>
<td>0.03</td>
<td>3.55</td>
<td>0.055</td>
<td>0.010</td>
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<tr>
<td>SAE 4140</td>
<td>0.41</td>
<td>0.23</td>
<td>0.82</td>
<td>0.05</td>
<td>0.16</td>
<td>-</td>
<td>0.018</td>
<td>0.005</td>
</tr>
<tr>
<td>SAE 4340</td>
<td>0.40</td>
<td>0.29</td>
<td>0.82</td>
<td>0.85</td>
<td>0.25</td>
<td>1.72</td>
<td>0.017</td>
<td>0.010</td>
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<tr>
<td>SAE 4640</td>
<td>0.42</td>
<td>0.24</td>
<td>0.76</td>
<td>0.18</td>
<td>0.26</td>
<td>1.78</td>
<td>0.032</td>
<td>0.008</td>
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<tr>
<td>SAE 5145</td>
<td>0.45</td>
<td>0.17</td>
<td>0.68</td>
<td>0.95</td>
<td>0.02</td>
<td>0.04</td>
<td>0.024</td>
<td>0.001</td>
</tr>
</tbody>
</table>

~1%Cr

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**Diagram:**

- **Hardened to martensite**
- **Hardened to 40 HRC**

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Strength of Martensite

Martensite strengthening mechanisms:

- Fine grain size
- Solid solution hardening
- Precipitation hardening
- Dislocation hardening

Tempering of Martensite

Martensitic steels containing retained austenite obtained after quenching in water and liquid nitrogen treatment.

<table>
<thead>
<tr>
<th>Alloy ID</th>
<th>C</th>
<th>Cr</th>
<th>Mo</th>
<th>Mn</th>
<th>Ni</th>
<th>Cu</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>LA (low-alloy)</td>
<td>0.38</td>
<td>1.03</td>
<td>0.14</td>
<td>0.65</td>
<td>0.21</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>HC (high-carbon)</td>
<td>1.21</td>
<td>0.09</td>
<td>0.01</td>
<td>0.26</td>
<td>0.08</td>
<td>0.12</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Magnetic saturation measurements

- Demagnetization and contraction due to carbide formation reactions
- Magnetization and expansion due to retained austenite decomposition
- Temperature ranges associated with tempering reactions change with the heating rate/holding time.
Tempering of Martensite

Lath martensite in a Fe-0.2C steel with a packet size of 8.2 μm

Tempering of Martensite

Tensile curves of 43XX series steels tempered at various temperatures for one hour

- **4330 steel**
  - 1 hr temper

- **4340 steel**
  - 1 hr temper

- **4350 steel**
  - 1 hr temper

Tempering of Martensite

1722 MPa  250,000
1379 MPa  200,000
1033 MPa  150,000
689 MPa   100,000

Tensile Strength  Yield Point
Reduction of Area  Elongation

Typical AISI 4340 applications:
Power transmission gears and shafts, heavy-duty shafts such as aircraft landing gear, pins

1 ksi = 1000 psi = 6.89 MPa

°C = \frac{5}{9} (F-32)

Tempering and Toughness

Phase content, %

<table>
<thead>
<tr>
<th>M</th>
<th>B</th>
<th>F+P</th>
<th>Degree of hardening</th>
<th>Test Temp., °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>95</td>
<td>5</td>
<td>-</td>
<td>1,00</td>
<td>0</td>
</tr>
<tr>
<td>-</td>
<td>100</td>
<td>-</td>
<td>0,76</td>
<td>△</td>
</tr>
<tr>
<td>-</td>
<td>35</td>
<td>65</td>
<td>0,51</td>
<td>●</td>
</tr>
</tbody>
</table>

Impact Energy, J

Hardness after Tempering, HV

42CrMo4 Steel
Tempering and Toughness

Fe-0.49C-0.79Mn-0.023P-0.023S-0.22Si-0.002Al

Hardened and tempered at 704 °C

Hardened and tempered at 621 °C

Hardened and tempered at 538 °C

As-received

Impact Energy, ft-lb

Test Temperature, °C

1 foot pound = 1.36 joules
Mechanical Properties of Martensite

**50CrV4 Steel**

![Graph showing mechanical properties](image)

- **UTS, MPa**
- **YS, MPa**
- **Elongation, %**
- **Reduction of Area, %**
- **Impact Energy, J**

**Impact Test Temperature, °C**

100% M
40% (F+P)
60% M
## SAE/AISI Designations

<table>
<thead>
<tr>
<th>SAE designation</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1xxx</td>
<td>Carbon steels</td>
</tr>
<tr>
<td>2xxx</td>
<td>Nickel steels</td>
</tr>
<tr>
<td>3xxx</td>
<td>Nickel-chromium steels</td>
</tr>
<tr>
<td>4xxx</td>
<td>Molybdenum steels</td>
</tr>
<tr>
<td>5xxx</td>
<td>Chromium steels</td>
</tr>
<tr>
<td>6xxx</td>
<td>Chromium-vanadium steels</td>
</tr>
<tr>
<td>7xxx</td>
<td>Tungsten steels</td>
</tr>
<tr>
<td>8xxx</td>
<td>Nickel-chromium-molybdenum steels</td>
</tr>
<tr>
<td>9xxx</td>
<td>Silicon-manganese steels</td>
</tr>
</tbody>
</table>

Example compositions and mechanical properties of engineering steels are provided in the last two slides of this lecture.
Due to their lower susceptibility to embrittlement and loss of ductility during tempering (temper embrittlement), Ni-Cr-Mo-alloyed Q&T steels are very popular in engineering applications.
Mechanical Properties vs. Microstructure

Influence of the microstructure (achieved by heat treatment control) on the mechanical properties of Q&T steels. Specimens were taken at a distance of 12.5 mm from the surface of 80 mm-diameter bars.

**Ck 45 (C45E, SAE 1045)**
- 0.42-0.45C
- 0.50-0.80Mn

**42 CrMo4 (SAE 4140)**
- 0.38-0.45C
- 0.60-0.90Mn
- 0.90-1.20Cr
- 0.15-0.30Mo

Test Temperature:
- Q&T
- Normalized
- Annealed
- Hot Deformed

Impact Energy, J

Impact Energy, J vs. Microstructure

Mechanical Properties

**Influence of carbon content on the toughness properties of Q&T steels of equal strength**

**Steels tempered 2 hrs between 450 °C and 750 °C**

Fatigue Strength

Influence of the fraction of martensite in the as-hardened state on the fatigue strength of various steels quenched and tempered to an identical hardness level of 36 HRC.

Martensite Content in the Microstructure, %

Fatigue Strength, MPa

Alloying Elements

**Iron**
- 0.030-0.035C
- 0.05-0.07Si
- 0.03-0.06Mn
- 0.01-0.02S
- 0.005-0.008P
- 0.07-0.15Cu

**Steel**
- 0.39-0.41C
- 0.26-0.36Si
- 0.60-0.66Mn
- 0.02-0.03S
- 0.018-0.025P
Normalizing of forgings:
- Microstructure homogenization
- Grain size refinement
- Better response to the subsequent quenching and tempering heat treatment
- Stress relieving
- Machinability

Grain size refinement of a Q&T steel (26 NiCrMoV 14 5) by multiple austenitization and transformation

Austenitization temperature: 840 °C
Expansion during Martensite Formation

Dimensional change of a SAE 4340 steel upon austenitization at 845 °C and subsequent cooling to room temperature.

In presence of large through-thickness temperature gradients, the expansion associated with martensitic transformation may lead to cracking and/or lowered fatigue strength.
Stress Evolution during Cooling

Temperature vs. Time diagram showing:
- Temperatures $T_1$ and $T_2$
- $Ae_3$ transformation
- $M_s$, $M_f$ transformation points
- Core and surface cooling curves
- Stress evolution with compression and tension
- Martensite and Austenite phases
- Transformed phases
Martempering

Isothermal holding at temperatures just above the $M_s$ temperature in order to equalize temperatures at different sections. This aims at avoiding distortion and cracking during the subsequent cooling below $M_s$ temperature.
Quench Embrittlement

The conditions for quench embrittlement, an intergranular mechanism of brittle fracture, develop in high-carbon steels during austenitizing or during quenching, i.e. this embrittlement is not caused by tempering. Thus, the term quench embrittlement has been used to describe a form of brittle fracture in order to differentiate it from the embrittlement mechanisms that occur after tempering. Characteristics of quench embrittlement:

- Intergranular fracture
- Hardened steel with more than about 0.5%C highly susceptible
- Presence of cementite and P in prior austenite grain boundaries.
- Higher sensitivity in presence of P (possibly due to reduced solubility of C in austenite and easier cementite formation during austenitization)
- Intergranular fracture of hypereutectoid steels may be avoided by intercritical austenitization in the austenite/cementite phase field prior to quenching. The carbide particles retained during such austenitizing treatments lower the carbon content to below that which produces intergranular fracture.
Quench Embrittlement

Combinations of C and P content leading to intergranular fracture in martensitic steels tempered at low temperatures.

Intergranular fracture (quench embrittlement)

No intergranular fracture

Tempered Martensite Embrittlement (TME)

Tempered martensite embrittlement (TME) is a microstructural condition that lowers the toughness and fracture resistance of hardened steels tempered between 200 and 400 °C. As a result of this embrittlement, the tempering range between 260 °C and 370 °C (500 and 700 °F) is generally avoided in commercial practice.

Charpy V-notch Number (CVN) impact energy as a function of tempering temperature for three medium-carbon steels, 4130, 4140 and 4150, and a high-carbon steel, 52100. Each steel has a low P and a high P variant. The phosphorus levels in the 41xx steels were 0.02 and 0.002\% and for the 52100 steel, 0.23 and 0.09\%.

Note: the hyper-eutectoid 52100 steel has been intercritically austenitized at 850 °C to produce a microstructure with spheroidized carbide particles not sensitive to intergranular fracture due to quench embrittlement.
Tempered Martensite Embrittlement (TME)

Fracture mode:
- Ductile
- Cleavage facets and microvoids
- Inter-granular

Tempered Martensite Embrittlement (TME) range

Tempered Martensite Embrittlement (TME)

Length changes associated with tempering reactions (tempering stages I and III) in as-quenched martensitic-austenitic specimens with various retained austenite contents (retained austenite content increases with C content)

Corresponding power consumption curves indicating release of the latent heat of transformation during the decomposition of retained austenite to bainite (stage II)

Effect of Si on Cementite Formation

As-quenched martensitic specimens containing retained austenite

Silicon effectively postpones the cementite formation range to higher temperatures
Tempered Martensite Embrittlement (TME)

- The reduced impact toughness associated with TME is associated with three different modes of fracture (transgranular, ductile, intergranular) the dominance of which depends on the carbon and phosphorus contents of hardened steels.
- The common feature of all the fracture mechanisms is the formation of cementite in the second and early third stage of tempering.
- Although phosphorus may have a worsening effect, the root cause of TME is the formation of new distributions of cementite produced by second- and early third-stage of tempering.
- 300M steel has a chemical composition almost identical to 4340 but it contains a higher silicon content between 1.45 and 1.8%. Higher Si in 300 M is thought to increase the temperatures at which cementite begins to form and allows to conduct the 1st stage tempering of 300M (tempering without cementite formation) at higher temperatures than in 4340.
Temper Embrittlement (TE)

Temper embrittlement (TE) is an embrittlement condition that develops in hardened carbon and alloy steels after tempering for relatively long times or cooling slowly through the temperature range of 375-575 °C. In view of the relatively long times required for TE to develop, heavy steel sections such as large shafts and rotors for power-generating equipment which cool slowly are most sensitive to TE.

SAE 3140 steel, containing nominally 1.15% Ni and 0.65% Cr, embrittled by both isothermal tempering and slow cooling through the critical tempering temperature range

Temper Embrittlement (TE)

- **TE kinetics follow C-curve behavior with tempering time and temperature, with a nose or minimum time for embrittlement at about 550 °C.** It takes about an hour at 550 °C for the first increase in transition temperature to be noticeable, and several hundred hours for the first signs of embrittlement at around 375 °C, the lower temperature range for TE.

- Temper embrittlement is **reversible**, and de-embrittlement may occur on heating to above around 575 °C for only a few minutes.

- **Specific impurities** must be present for a steel to be susceptible. The impurities most detrimental are antimony, phosphorus, tin, and arsenic. Relatively small amounts of these elements, on the order of 100 ppm (0.01%) or less, have been shown to cause TE.

- **Silicon** and manganese in large amounts also appear to be detrimental. As long as the manganese content is held below 0.5%, plain carbon steels are not very susceptible to TE. **Alloy steels are most susceptible**, especially the chromium-nickel steels which are frequently used for heavy rotors.

- **Molybdenum** reduces the susceptibility to TE and, in amounts of 0.5% or less, is an important alloying element added to steels to minimize TE.

- **TE appears to be related to the segregation of impurity elements to prior austenite grain boundaries at relatively high tempering temperatures** (intergranular fracture).

Temper Embrittlement (TE)

Effect of Mo on the temper embrittlement of a Ni-Cr-Mo-V steel. $\Delta T_{\text{DBTT}}$ represent the difference between the transition temperature of steel after the following tempering treatments, cycle 1 without temper embrittlement and cycle 2 susceptible to temper embrittlement:

**Cycle 1:** 4 hrs 600 °C $\rightarrow$ water quench

**Cycle 2:** 4 hrs 600 °C $\rightarrow$ 15 hrs 540 °C $\rightarrow$ 24 hrs 525 °C $\rightarrow$ 48 hrs 495 °C $\rightarrow$ 72 hrs 465 °C $\rightarrow$ air cooled from 315 °C

$\Delta T_{\text{DBTT}} = \text{DBTT}_{\text{cycle2}} - \text{DBTT}_{\text{cycle 1}}$

(Fe-0.23C-0.29Si-0.39Mn-0.013P-0.012S-3.40Ni-1.85Cr-0.007Sn-0.14V)
Temper Embrittlement (TE)

Reduction of areas measured from tensile specimens of the 43xx steels tempered for 1 hour and 10 hours. Reduction of area of the specimens tempered for one hour show essentially a continuous increase with increasing tempering temperature. However, the specimens tempered for 10 h show a sharp drop in reduction of area at 500 °C. Temper embrittlement is associated with the co-segregation of substitutional alloying elements and impurity elements such as phosphorus to prior austenite grain boundaries.

### Chemical Compositions of Selected Eng. Steels

**SAE designations**

<table>
<thead>
<tr>
<th></th>
<th>4140</th>
<th>4142</th>
<th>4145</th>
<th>4150</th>
<th>4150 RES</th>
<th>4320</th>
<th>4330V</th>
<th>4340</th>
<th>4350</th>
<th>4620</th>
<th>4820</th>
<th>6150</th>
<th>8620</th>
<th>8630</th>
<th>8822</th>
<th>9310</th>
</tr>
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<tbody>
<tr>
<td><strong>C</strong></td>
<td>0.38-0.43</td>
<td>0.40-0.45</td>
<td>0.43-0.48</td>
<td>0.48-0.53</td>
<td>0.48-0.53</td>
<td>0.17-0.22</td>
<td>0.28-0.33</td>
<td>0.38-0.43</td>
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<td>0.07-0.13</td>
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<tr>
<td><strong>Mn</strong></td>
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<td>0.75-1.00</td>
<td>0.75-1.00</td>
<td>0.75-1.30</td>
<td>0.75-1.30</td>
<td>0.45-0.65</td>
<td>0.75-1.00</td>
<td>0.60-0.80</td>
<td>0.60-0.80</td>
<td>0.45-0.65</td>
<td>0.50-0.70</td>
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<td>0.40-0.70</td>
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</tr>
<tr>
<td><strong>P</strong></td>
<td>0.030</td>
<td>0.030</td>
<td>0.030</td>
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## Chemical Compositions and Properties

### Former DIN designations

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<th>Mo</th>
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### Mechanical Properties

#### Diameter between 16 and 40 mm

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<th>$Z$</th>
<th>$A_v$&lt;sup&gt;b&lt;/sup&gt;</th>
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#### Diameter between 16 and 40 mm

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<th>$A_t$</th>
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