

---

---

# Index

## A

### academic research and development

Grain Refinement of DP Steel, 211–212(F,T)

Microstructure Evolution in TWIP Steel, 210–211(F)

Structure and Mechanical Properties of Fe-Mn Alloys, 205–210(F)

### active binders, 232–235(F)

binder force trajectories, 232, 233(F)

DP 590 U-channel forming, 232–234, 233(F), 234(F)

flexible binder technology, 234–235, 235(F)

springback, 232

system, 232

### active drawbeads, 230–231, 231(F). *See*

*also* binders and draw beads

bead penetration, 231

binder restraining forces, 230–231

restraining forces, 231

strain distribution, sheet metal forming, 230

tooling, 231, 231(F)

### advanced high-strength steel (AHSS). *See*

*also* individual grades

AISI definitions, 42, 43(T)

applications, 59, 159–169(F)

attributes, 15, 71–94(F)

content, new car, 19

costs, 16, 16(T)

CP grades, 47

CP steels (*see* complex-phase (CP) steels)

crushing zone, 79

downgaging, 59

DP grades, 47

DP steels (*see* dual-phase (DP) steels)

drawbead restraining forces, 231

energy-absorption capabilities, 89, 90(F)

### equibiaxial hemispherical stretch

forming, 81, 83(F)

first and second generation of AHSS, location of, 18(F)

first generation (*see* AHSS generations)

flat rolled application, 16

flat rolled steel delivered (2010), 16(F)

FSV program, 19

fundamentals, 1–2, 46–47

generations (*see* AHSS generations)

grade classification, 60(T)

grades, 47–50, 154(F)

identifying system, 59–60

in strength-elongation space, 14, 14(F)

introduction, 17–20(F)

manufacturing challenges, 1–2

mechanical properties, 153–154, 154(T)

first generation, 65(T)

values of, 66, 66(T)

microstructure, 59

CCT diagram, 65

cooling routes, 65(F)

development, 64–65, 65(F)

first generation, 65(T)

HSS, difference between, 15

overview, 19–20

thermal processing routes, 65, 65(F)

MS grades, 48 (*see* martensitic (MS) grades)

MS steels (*see* martensitic (MS) steels)

nomenclature, 59–60

overview, 17–18

property trends, 65–69(F), 70(F)

engineering stress-strain curves,

comparison, 67, 67(F)

forming limit diagrams, comparison

of, 69, 70(F)

strength or hardness and formability,

relationship between, 69, 69(F)

tensile strength and elongation,

relationship between, 66, 66(F)

recycling to BOF production cycle, 260

- advanced high-strength steel (AHSS).
  - (continued)
  - safety zone, 79
  - second generation (*see* AHSS generations)
  - springback, 180
  - strain-hardening, 46, 59, 72–75(F)
  - strain-hardening capacity, 59
  - strength, determining, 72
  - strength-elongation relationships, 49(F)
  - strengthening mechanisms, 18
  - tensile strength, 59
  - thermomechanical processing (*see* AHSS thermomechanical processing)
  - third generation (*see* third generation AHSS)
  - toughness, 154(F)
  - TRIP grades, 47–48
  - TRIP steels (*see* transformation-induced plasticity (TRIP) steels)
  - twin boundary hardening, 56
  - twinning-induced plasticity (TWIP) grades, 48
  - ULSAB-AVC Consortium identification standard, 59
  - UTS, 59–60
  - work-hardening, 80, 178
  - YS, 59–60
- Advanced High-Strength Steel
  - Applications: Design and Stamping Process Guidelines (Auto Steel Partnership (ASW)), 215–216
- Advanced High-Strength Steels
  - Application Guidelines, Version 4.1 (WorldAutoSteel), 215, 216, 220–221
- advanced steels, 17–20(F), 61. *See also* steel industry projects
- aging process, 91–93(F)
- AHSS economics, 261
- AHSS generations
  - first generation
    - applications, 60
    - ferrite, 18, 60
    - grades, 60
    - location of, 18(F)
    - location of, strength-elongation space, 18(F)
    - mechanical properties, 65(T)
    - microstructure, 60(T), 65(T)
    - overview, 18–19, 263
    - tensile strength range, 60(T)
    - tensile strength versus elongation chart, 61(F), 62(F)
    - toughness, 90
  - second generation, 60–61, 62
    - alloying elements, 61
    - applications, 61
    - cost, 18
    - grades, 60–61
    - location of, 18(F)
    - location of, strength-elongation space, 18–19, 18(F)
    - microstructure, 61(T), 264(T)
    - overview, 60–61(F,T), 62(F), 263
    - tensile strength ranges, 49, 49(T), 61(T)
    - toughness, 90
  - third generation (*see* third generation AHSS)
- thermomechanical processing
  - advanced steels, 17
  - annealing, 63
  - bainite isothermal transformation treatment, 64
  - continuously annealed products, 63
  - CP steels, 64
  - DP steels, 64
  - heat treatment, 63
  - hot dip coated products, 63
  - hot-rolled products, 63
  - intercritical annealing, 63, 64
  - MS steels, 64
  - processing schemes, AHSS grades, 64
  - TRIP steels, 64
  - ultrafine-grained alloy, 64
- air cushions, 184, 232
- aircraft industry, 152, 159, 170
- AISI. *See* American Iron and Steel Institute (AISI)
- AISI/SAE
  - composition systems, low alloy steels, 44(T)
  - composition systems, plain carbon steel, 44(T)
  - designation systems, low alloy steels, 44(T)
  - designation systems, plain carbon steel, 44(T)
- AKDQ steels. *See* aluminum-killed drawing quality (AKDQ) steels
- Alloy Stainless Products (ASP), 265–266
- alloy steels, 26, 44
- alloying, 25–26, 45
- alloying elements
  - alloy additions, steels, 41–42
  - alloy steels, 44
  - AUST SS, 48, 151, 152
  - CP grades, 47
  - dependence of the eutectoid temperature on alloy concentration, 25(F)
  - DP steels, 98
  - HSLA, 44, 45

- MS grades, 48
- MS steels, 128
- precipitation-hardening stainless steels, 46
- second generation AHSS, 61
- TRIP steels, 115
- TWIP steels, 135, 137
- aluminum
  - AUST SS, 151
  - automotive industry, 10
  - DSTC process, 271
  - embodied energy, 258, 258(T)
  - energy and emissions for producing, 253, 253(T)
  - energy required for ore conversion and embodied energy, 253, 253(T)
  - fuel consumption, 258
  - low-carbon steel, versus, 258–259
  - stainless steels, 45
  - TRIP steels, 115, 117
  - TWIP steels, 135
- aluminum alloys
  - ductility, 12, 13(F)
  - fuel efficiency, improving, 9
  - steel, cost versus, 11–12
  - yield strength, 12, 13(F)
- aluminum-killed drawing quality (AKDQ) steels, 180, 182, 217
- American Iron and Steel Institute (AISI), 42, 43(T), 170, 200, 252–253, 265–266
- American National Standards Institute (ANSI), 220
- American Welding Society (AWS), 220
- annealing
  - AUST SS, 153, 155
  - carbon steels, 57
  - continuously annealed products, 63
  - conventional, 38
  - DP steels, 100–101, 101(F)
  - ferrite, 38
  - fundamentals, 57, 57(F)
  - grain structure, 57(F)
  - intercritical annealing process, 64
  - intercritical temperature on the carbon content of austenite, effect of, 63(F)
  - recovery, 57
  - recrystallization, 57
  - thermomechanical processing, 63
  - TRIP steels, 118
  - TWIP steels, 139
- annealing twins, 56, 135, 207
- anti-intrusion applications, 20
- applications (AHSS)
  - automotive (*see* automotive applications)
  - nonautomotive (*see* nonautomotive applications)
- overview, 159
- utilization and trend (vehicles), 171–175(F)
  - CAFE regulations, 172–173
  - Ducker Worldwide, 171, 172–173
  - flat rolled AHSS, 172–173, 173(F)
  - FSV program, 174–175
  - North American light vehicles, 171(F), 172, 174(F)
- ASP. *See* Auto Steel Partnership (ASP)
- atomic planes, 136
- atoms
  - bainite isothermal transformation treatment, 64
  - bake hardening, 91
  - carbon atoms, 24, 26, 55, 64, 128, 146
  - dislocations, 51
  - heat treatment, 26
  - interstitial atoms, 54, 54(F)
  - iron atoms, 132
  - martensitic transformation, 33
  - MS steels, 127, 128
  - nanosteels, 271
  - nitrogen atoms, 91
  - quench hardening, 55
  - room-temperature dynamic strain aging, 146–147
  - solid-solution strengthening, 54
  - solute atoms, 54
  - stacking faults, 136
  - substitutional atoms, 54, 54(F)
  - twinning, deformation by, 52
  - twins, 135, 136(F)
- AUST SS. *See* austenitic stainless steels (AUST SS)
- austempering
  - conventional, 38
  - TTT diagram, 37, 37(F)
- austenite
  - alloying elements, 24
  - cooling, effects of, 27
  - definition of, 23, 24
  - isothermal transformation of eutectoid steel from austenite to pearlite, 29(F)
  - magnetic properties, 24
  - martensite, transformation to, 30(F), 32
  - to pearlite, 27
  - transformation of, 27
- austenitic stainless steels (AUST SS)
  - alloying elements, 48, 151, 152
  - applications, 46, 152, 157, 158(T)
  - attributes, 157–158
  - austenitizing elements, 45, 48
  - automotive industry, 158, 158(T)
  - chromium, 45
  - cold working, 48, 151
  - compositions, 152–153, 153(T), 154(T)

- austenitic stainless steels (AUST SS)
  - (continued)
  - corrosion resistance, 48, 151
  - costs, 15–16, 16(T)
  - crash performance, 48
  - deformation mechanism, 153
  - ductility, 48, 153
  - ferrite, 151
  - formability, 155–156, 156(F)
    - annealed, 155
    - forming limit curves, 155, 156(F)
    - LDH test, 155–156, 156(F)
  - fundamentals, 45–46, 48
  - hardening, 46, 48, 151
  - iron, 45, 151
  - magnetic properties, 151
  - mechanical properties, 151–158(F,T)
    - appearance, 151
    - ductility, 48, 151, 154
    - formability, 151
    - hardening, 153
    - introduction, 45–46, 48
    - low maintenance cost, 151
    - mechanical properties, 154(T), 155(T)
    - recyclability, 151
    - strength, 151
    - strengthening, 153
    - tensile strength, 48, 153
    - toughness, 154–155, 155(T)
    - true stress-strain curves, 154(F)
    - uniaxial tensile tests, 154(F)
    - YS, 153
  - microstructures, 152
  - overview, 151–152
  - processing of, 153
  - slip, 153
  - strain-hardening, 154, 156
  - tensile strength, 48
  - welding, 197
- austenitic stainless steels (AUST SS),
  - types, 153(T)
  - type 302, 152(F)
  - type 304, 152, 154(T)
  - type 316, 152
  - type 321, 152
  - type 347, 152
  - type 900, 156(F)
- austenitization, 24, 24(F), 26
- austenitizing elements, 45, 48
- auto body structural components, 217–218
- Auto Steel Partnership (ASP)
  - ASP/USAMP, 205
  - design guidelines, 215–216
  - development and deployment of AHSS technology, 199
  - GMAW, establish design guidelines for, 219–220, 219(F), 220(F)
  - ICME, 273
  - partnership linkages, 205(F)
  - resistance welding performance study, 218–219, 218(F)
  - third generation AHSS, 266
  - welding guidelines, chassis structures, 220
  - welding performance of HSS, 217–218
- Automotive Application Council, 205
- automotive applications
  - AHSS content per vehicle, 160
  - BIW structure, 160–161, 162(F)
  - closure, 161, 164, 166(F)
  - criteria, 159–160
  - mapping vehicles application to steel grades, 161, 161(F)
  - passenger car component groups, 160–162
  - representative cases
    - 2011 FutureSteelVehicle (FSV), 167–169, 169(F)
    - 2012 Chrysler Dodge Dart, 163, 164(F)
    - 2013 Ford Fusion, 164–166, 166(F), 167(F)
    - 2013 GM Cadillac ATS, 163–164, 165(F)
    - 2013 GM Chevrolet Sonic, 166–167, 168(F)
    - battery electric vehicle (BEV), 169(F)
    - overview, 163
    - strength-ductility chart, 161, 161(F)
    - structural components, typical car, 161, 162(F)
- automotive industry. *See also* Global Automotive
  - Chrysler Group, 203, 205
  - Daimler Benz plant, 235
  - Ford Motor Company, 157, 157(F), 256, 256(T)
  - General Motors Company, 203, 205, 273
  - Mazda (2008 Mazda 2), 168
  - Mercedes (2008 C Class), 168
- Industry; steels
  - aluminum, 10
  - AUST SS, 158, 158(T)
  - body panels, reducing springback, 185
  - CAFE, 2
  - dimpling, 194
  - downgaging, 2
  - drivers and solutions, 2
  - fatigue life, 160
  - fuel efficiency requirements,
    - achieving, 8–9, 8(F)
  - HSS, 10
  - lightweighting, 193

- metallurgy and microstructural designs, developing, 265–266
  - spectrum of steel categories, 13–15, 14(F)
  - steels currently used, 49–50, 49(T)
  - third generation AHSS availability target, 265, 265(F)
  - welding, 195
  - Auto/Steel Partnership/U.S. Automotive Materials Partnership (ASP/USAMP), 205, 205(F), 273
- ## B
- bainite
    - definition of, 23
    - ferrite, 27
    - isothermal transformation of eutectoid steel from austenite to bainite, 27–28, 29(F)
    - knee, the, 27
  - bainite isothermal transformation treatment, 64
  - bake hardening, 91–93(F)
    - carbon, 91
    - deformation characteristics, 91, 92(F)
    - DP steels, 92, 92(F), 93
    - nitrogen atoms, 91
    - overview, 91
    - process, 92, 92(F)
    - TRIP steels, 92–93, 92(F), 123
    - YS, increasing, 44
  - bake hardening effect, 44, 47, 97, 123
  - bake-hardenable (BH) steels
    - BH 210, 186, 186(F)
    - applications, 44
    - energy-absorption capabilities, 89, 90(F)
    - fundamentals, 44
    - in strength-elongation space, 13–14, 14(F)
  - bake-hardening effect
    - DP grades, 47
    - DP steels, 97
  - basic oxygen furnace (BOF), 251–252
    - AHSS, recycling to, 260
    - iron ore, 251–252
  - battery electric vehicle (BEV), 169(F)
  - BH steel. *See* bake-hardenable (BH) steels
  - binder force, 228
  - binder force trajectories, 228, 232, 233(F), 241–242, 242(F)
  - binders (blankholders). *See* binders and draw beads
  - binders and draw beads, 187–189(F)
    - active binders, 232–235(F)
    - bead penetration, 188, 231
    - bending force, 188
    - binder restraining forces, 230–231
    - binders (blankholders), 187
    - draw bead action, stages, 188
    - flat binders, 188
    - flexible binders, 236–243(F)
    - friction force, 188
    - inadequate binder forces, 189, 189(F)
    - lock beads, 187–188
    - metal flow, controlling, 189
    - restraining force, 188
    - sheet metal forming system, 188, 188(F)
    - stamping, 227
    - traditional stamping, 188–189
  - BIW. *See* body-in-white (BIW)
  - blankholder, 227, 227(F). *See also* binders and draw beads
  - body-centered cubic (bcc)
    - carbon steel, 23
    - deformation twinning, 53
    - duplex (ferritic-austenitic) stainless steels, 46
    - ferrite, 24
    - ferritic stainless steels, 45
    - heat treatment, 26
    - iron, 23
    - mechanical twins, 135
    - MS steels, 127
    - phase transformation of iron, 38
    - quench hardening, 55
    - twin boundary hardening, 56
  - body-in-white (BIW)
    - 2012 Chrysler Dodge Dart, 164(F)
    - 2013 GM Cadillac ATS, 163–164, 165(F)
    - 2013 GM Chevrolet Sonic, 168(F)
    - ASP document, 216
    - defined, 160–161
    - LDC, 21, 21(F)
    - passenger car, 162(F)
    - Porsche Cayenne, 163(F)
    - steel content, light vehicles, 16–17, 17(F)
  - BOF. *See* basic oxygen furnace (BOF)
  - boron, 48, 128
  - boundary hardening, 56, 72, 272
  - brittle fracture, 136
- ## C
- CAFE. *See* Corporate Average Fuel Economy (CAFE)
  - CAL process. *See* continuous annealing line (CAL) process
  - carbide precipitation, 117, 153
  - carbides, 45, 89, 153, 197, 269, 272

- carbon
  - atoms, 24, 48, 55, 64, 127, 146
  - austenite, 26
  - austenitizing steel, 38
  - bake hardening, 91
  - DP steels, 47, 96, 98
  - DSTC process, 270
  - emissions, 200, 257
  - ferrite, 25
  - ferrite to austenite, 63
  - ferritic stainless steels, 45
  - intercritical annealing, 63
  - iron, 253
  - iron-phase diagram, 25
  - martensitic transformation, 33
  - MS steels, 45, 48
  - partitioning, 269, 270
  - Q&P process, 269
  - quench hardening, 55
  - sensitization, 197
  - solubility limit in iron, 24, 25
  - stainless steels, 45
  - steels, 23, 25, 26
  - TRIP steels, 116–117, 119
  - TTT diagram, 28
  - TWIP steels, 140–141, 142
- carbon content
  - AUST SS, 152
  - carbide precipitation, 117
  - carbon steel, 23, 24, 24(F), 40–41, 41(F)
  - CCT diagram, 36, 36(F)
  - DP steels, 99, 211
  - ductility, 39
  - Fe-C phase diagram, 23
  - ferrite, 25
  - ferritic stainless steels, 45
  - high-carbon steel, 44
  - HSLA steels, 44
  - intercritical temperature, 63, 63(F)
  - low-carbon steel, 44
  - medium-carbon steel, 44
  - microstructural features, 27
  - MS grades, 48
  - MS steels, 45, 127, 128
  - pearlite, 23
  - plain carbon steels, 39, 39(F)
  - Q&P process, 269
  - recycling, 260–261
  - sensitization effect, 197
  - stainless steels, 45
  - steel fundamentals, 23, 24, 25, 44
  - tensile strength, 41(F)
  - thermomechanical processing, AHSS, 63, 63(F)
  - third generation AHSS, 264
  - toughness, 39
  - TRIP steels, 64, 116–117, 118, 118(F), 119
  - TWIP steels, 135, 139, 140–141
- carbon dioxide (CO<sub>2</sub>)
  - electricity, 4–5, 5(F)
  - emissions by sectors, 5(F)
  - transportation sector, 5–6
- carbon footprint
  - carbon footprint, 6(T)
  - CO<sub>2</sub> emissions, 6, 6(T)
  - light vehicles, 1975–2010, 6, 6(T)
  - steels, environmentally friendly and sustainable materials, 251, 251(F)
- carbon partitioning, 270, 270(F)
- carbon steel
  - carbon content, 23
  - carbon content, effect on tensile strength and hardness, 40–41, 41(F)
  - cooling, 26
  - Fe-C phase diagram, 24, 24(F)
  - ferrite, 24
  - forming limit curves, 155, 156(F)
  - fundamentals, 42, 44
  - high-carbon steel, 44
  - low-carbon steel, 44
  - medium-carbon steel, 44
  - microstructures and mechanical attributes, 35(T)
  - uniaxial tensile tests, 154(F)
- carbon steels
  - annealing, 57
  - hot rolling, 56, 57(F)
- carbonitrides, 45
- cast iron, 9, 10(T)
- CCR. *See* critical cooling rate (CCR)
- CCT. *See* continuous cooling transformation (CCT) diagram
- cementite (iron carbide Fe<sub>3</sub>C), 23, 24
- chemical vapor deposition (CVD), 191, 192
- chromium
  - alloy steels, 44
  - AUST SS, 48, 151, 152
  - duplex (ferritic-austenitic) stainless steels, 46
  - HSLA, 44
  - MS grades, 48
  - MS steels, 128
  - precipitation-hardening stainless steels, 46
  - second generation AHSS, 61
  - stainless steels, 45
- chromium carbide, 197
- closed-loop control system, 238–239, 239(F)
- closed-loop system, 228, 229–230, 230(F)
- closures, 161
- CO<sub>2</sub>. *See* carbon dioxide (CO<sub>2</sub>)
- CO<sub>2</sub> emissions
  - carbon footprint, 6, 6(T)
  - electricity, 4–5, 5(F)

- gallon of fuel, 6, 6(T)
- sustainability, 250
- U.S transportation sector, 5–6
- vehicles, 5, 5(F)
- CO<sub>2</sub> equivalents, 259
- CO<sub>2</sub> footprint, 250
- coating processes
  - costs, 192
  - CVD, 191, 192
  - PACVD, 191
  - process, 191
  - PVD, 191
  - TD, 191
- coatings
  - cost, offsetting, 192
  - die coatings, 190
  - packaging steels, 171
  - PVD, 191
  - temperature ranges, 191
  - tool material and die wear, 190–192, 191(F)
  - TRIP steels, 121, 121(T)
- cobalt, 45
- coefficient of expansion, 197
- cold rolled sheets, 98
- cold rolling, 56, 57(F)
- cold working, 46, 48, 90, 151
- complex-phase (CP) grades
  - alloying elements, 47
  - applications, 47
  - microstructure, 47
  - properties, 47
  - tensile strengths, 47
- complex-phase (CP) steels
  - applications, 47
  - attributes, 112
  - chemical composition, 108
  - compositions, 107, 108(T)
  - deformation mechanisms, 108–109
  - ductility, 111
  - ferrite, 107, 109
  - FLD, 111–112, 112(F)
  - formability of, 111–112(F)
  - fundamentals, 47
  - mechanical properties, 109–111(F,T)
    - downgaging, 109
    - ductility, 109
    - engineering stress-strain curves, 10(F)
    - mechanical properties, 109(T)
    - S-N* curves, 110, 111(F)
    - tensile strength ranges, 109
    - tensile strength-total elongation space, 109(F)
    - true stress-strain curves, 110, 110(F)
  - microstructures, 107, 108(F)
  - niobium, 107, 108
  - processing, 107–108, 118(F)
  - properties, 47
  - S-N* curve, 77(F)
  - in strength-elongation space, 14, 14(F)
  - strengthening mechanisms, 109
  - tensile strength-total elongation space, 109, 109(F)
  - thermomechanical processing, 64
  - titanium, 107, 108
  - total elongation, 109
  - vanadium, 107, 108
  - welding, 197
- complex-phase (CP) steels, types
  - CP 590 SF, 112
  - CP 800, 112
  - CP 1000, 86–87(F)
  - CP 1000 SF, 87, 87(F), 112
- component thinning, 81
- composite materials
  - automotive industry, 10
  - fuel efficiency, improving, 9
- constant binder force (CBF), 234
- continuous annealing line (CAL) process, 101(F)
- continuous casting
  - advanced steels, 17
  - AUST SS, 153
  - deformation processing, 56, 57(F)
- continuous cooling, 28–32
  - eutectoid steel, microstructures resulting from fast and slow CCR, 30, 31(F), 32
  - superposition of the CCT diagram on the isothermal cooling (TTT) diagram, 30(F)
  - temperature histories of a continuous transformation diagram (CCT), 31(F)
  - temperature histories of an isothermal cooling diagram (TTT), 31(F)
- continuous cooling transformation (CCT) diagram, 31(F), 271
  - AHSS, 65, 65(F)
  - AISI/SAE 4340, 36, 36(F)
  - CCR for eutectoid steel, 33(F), 34(F)
  - cooling curves, 31(F)
  - high-strength, low-alloy steel AISI/SAE 4340, 36(F)
  - isothermal transformation curves, 28, 30(F)
  - knee, avoiding, 34, 36
  - martensite, 32
  - quenching, austenite to martensite, 34, 35(F)
  - temperature history, 30, 31(F)
  - thermal processing routes, AHSS, 65(F)
- copper
  - alloy steels, 44
  - AUST SS, 151
  - stainless steels, 45

Corporate Average Fuel Economy (CAFE)  
 automotive industry, drivers, 2  
 Energy Bill (2016 proposed standards),  
 7  
 future AHSS content, 172–173  
 corrosion resistance  
 AUST SS, 48, 151, 157  
 downgaging, 194  
 corrugation, 72, 194  
 CP grades. *See* complex-phase (CP) grades  
 CP steels. *See* complex-phase (CP) steels  
 CR TRIP steel, 121, 121(T)  
 cracks  
 S-N curve, 75, 76(F)  
 toughness, 89  
 crash performance, 20, 48  
 crashworthiness, 77–81(F)  
 assessing, 80  
 crushing zone, 78, 78(F), 79  
 definition of, 77  
 energy-absorbing capabilities  
 DP 350/600, 79, 79(F)  
 HSLA 350/450, 79, 79(F)  
 energy-absorbing materials,  
 requirements for, 80  
 occupant safety, 77–78  
 passenger compartment, 205  
 progressive crush zones, 78–79  
 regular buckling folds, 80, 80(F)  
 requirements, 79  
 safety zone, 78, 78(F), 79  
 total buckling structures, 80, 80(F)  
 TRIP steels, 80  
 TWIP steels, 80–81  
 critical cooling rate (CCR), 30  
 crushing zone, 78, 78(F), 79  
 crystal twins, 56  
 crystalline nanomaterials, 271–272  
 cup drawing, 186, 229  
 curl, 182–183, 183(F)  
 curl radius, 184, 185(F)  
 cutting tools, 88–89, 89(F)  
 CVD. *See* chemical vapor deposition  
 (CVD)

## D

deep drawing, 83–85(F)  
 cup height, variation for different types  
 and grades of steel, 85(F)  
 deep-drawn parts, 83  
 drawability, 85, 85(F)  
 flat-bottomed cups, 83–85(F)  
 flat-bottomed cups, tooling for, 83,  
 84(F), 85  
 LDR, 85, 85(F)  
 sheet metal, 83–85(F)

deformation mechanisms  
 dislocation glide, 50–52  
 twinning, 52–53, 52(F)  
 deformation processing, 56–57, 57(F)  
 deformation twinning, 53. *See also*  
 twinning  
 design guidelines  
 Advanced High-Strength Steel  
 Applications: Design and Stamping  
 Process Guidelines, 215–216  
 Advanced High-Strength Steels  
 Application Guidelines, Version  
 4.1, 215, 216  
 Auto Steel Partnership (ASP) document,  
 215–216  
 forming guidelines, 216–217  
 HSS, BIW applications, 216  
 overview, 215  
 performance evaluation, 221–224(F,T)  
 panel loaded in bending, 222, 222(F)  
 performance indices for car body  
 applications, 221–222, 222(T), 223  
 selection chart, 223–224, 223(F)  
 welding (*see* welding guidelines)  
 WorldAutoSteel document, 215, 216  
 diffusion  
 mechanism of, 26  
 temperature, effect of, 27  
 diffusionless process, 33  
 dimpling, 72, 194  
 dislocation glide  
 CP steels, 109  
 fundamentals, 50–52  
 plastic deformation, 56  
 strength, 72  
 structure-property relationships, 38  
 TWIP grades, 48  
 TWIP steels, 142  
 dislocation line, 53  
 dislocations, 50–51, 51(F). *See also*  
 dislocation glide  
 dispersion hardening, 54, 115  
 double-action press, 184  
 double-stabilization thermal cycle (DSTC)  
 process, 270–271, 271(F)  
 downgaging  
 AHSS, 59  
 automotive industry, 2  
 CP steels, 109  
 MS steels, 129  
 nonautomotive applications, 171  
 downgaging limits, 193–194  
 corrosion resistance, 194  
 ductility, loss of, 194  
 stiffness, 193–194  
 downsizing, 9  
 DP grades. *See* dual-phase (DP) grades  
 DP steels. *See* dual-phase (DP) steels



- draw beads. *See also* binders and draw beads
  - AHSS, 189
  - HSS, 189
  - purpose of, 187
  - run out, 189, 189(F)
  - types, 189(F)
- drawability, 85, 85(F)
- drawbead penetration, 184, 184(F)
- drawbead restraining forces
  - AHSS, 231
  - HSLA, 231
  - MILD steel, 231
- drawbeads, 81, 204. *See also* active drawbeads
- drawing quality steel (DQSK), 186, 186(F)
- DSTC process. *See* double-stabilization thermal cycle (DSTC) process
- dual-phase (DP) grades
  - bake-hardening effect, 47
  - formability, 47
  - heat treating practices, 47
  - martensite, 47
  - microstructure, 47
  - strain-hardening capabilities, 47
  - tensile strengths, 47
- dual-phase (DP) steels
  - advantages of, 95
  - applications, 106
  - attributes, 105–106
  - bake hardening, 92, 92(F), 93
  - carbon, 96, 98
  - cold rolled sheets, 98
  - commercial production, 100
  - composition and microstructure, 95–98(F,T)
    - alloying elements, 98
    - alloying elements, and effects of, 96(T)
    - bake-hardening effect, 97
    - chemical compositions, 98, 98(T)
    - grain size information, 97, 98(T)
    - grain sizes, 97, 97(F)
    - microstructure, 96(F)
    - strength levels, determining, 96
    - tensile data, 98(T)
    - UTS, 95, 97
  - continuous annealing, 100–101, 101(F)
  - deformation mechanisms, 102
  - energy-absorption capabilities, 89, 90(F)
  - ferrite, 47, 64, 73, 73(F), 95, 95(F), 98–99
  - FLD, 124(F)
  - formability of, 105, 105(F)
  - galvannealed (DP) steel, 101, 101(F)
  - Grain Refinement of DP Steel, 211–212(F,T)
  - heat treating practices, 96
- hot rolled sheets, 98
- hot rolling, 100, 100(F)
- intercritical annealing, 98, 99, 99(F)
- mechanical properties, 102–104(F,T)
  - DP types, 103(T)
  - engineering stress-strain curves, 102, 103(F)
  - fatigue curves, 104(F)
  - fatigue properties, 104
  - location in tensile strength-elongation space, 102(F)
  - tensile ranges, 102
  - total elongation ranges, 102
  - true stress-strain curves, 102–104, 103(F)
- microstructure, 98
- processing, 98–101(F)
- properties, 97
- quenching, 98
- S-N curve, 77(F)
- strain-hardening, 47, 92, 93(F), 97, 102
- strengthening effect, 101
- tensile strength-total elongation space, 102, 102(F)
- thermomechanical processing, 64
- time-temperature schedule, hot rolled DP steels, 119(F)
- total elongation, 97, 211(T)
- uniaxial tensile tests, 154(F)
- work-hardening, 73, 95, 105, 183
- work-hardening rate, 73
- dual-phase (DP) steels, types
  - DP 300/500, 179, 179(F)
  - DP 350/600, 73, 74(F), 79, 79(F), 179, 179(F), 183, 183(F)
  - DP 600, 83(F), 95(F), 104, 104(F), 124(F), 178, 178(F), 180, 183, 183(F), 217, 218
  - DP 750, 154(F), 156(F)
  - DP 780, 196, 217
  - DP 800, 154(F), 165, 218
  - DP 980, 86–87(F), 217, 218
  - DP 1000, 83(F), 165
  - welding, 196–197
- ductility
  - aluminum alloys, 12, 13(F)
  - AUST SS, 48, 153, 154
  - automotive applications, 161, 161(F)
  - carbon content, 39
  - CP steels, 109, 111
  - defined, 38
  - downgaging limits, 194
  - flexible rolling, 244–245
  - magnesium alloys, 12, 13(F)
  - martensite, 33
  - measuring, plain carbon steels, 39
  - MS steels, 129
  - percent elongation, 38

ductility (continued)  
 plain carbon steel, 39  
 reduction in area, 38  
 steels, 12, 13(F), 50(F)  
 third generation AHSS, 61–62(F), 263–264(F), 266–267(F,T), 268(F)  
 TWIP steels, 48  
 duplex (ferritic-austenitic) stainless steels  
 alloying elements, 46  
 ferrite, 46  
 fundamentals, 46  
 properties, 46  
 stress-corrosion cracking, 46

## E

economics, AHSS, 261  
 electric arc furnace (EAF), 251, 252  
 electricity, 4–5, 5(F)  
 electron backscatter diffraction (EBSD)  
 DSTC process, 271  
 Fe-24Mn, 209(F)  
 Fe-28Mn, 210  
 Fe-30Mn, 206–207, 207(F)  
 mechanical twins, 142(F)  
 embodied energy  
 aluminum, 258, 258(T)  
 chart, various metals, 253–256, 254(F)  
 CO<sub>2</sub> emissions, 253, 253(T)  
 defined, 250  
 iron, production process, 253  
 per unit strength, 255–256, 256(F)  
 steel, 258, 258(T)  
 sustainability, 250  
 typical vehicle, 257–258, 258(F)  
 emissions by sectors, 21  
 EMS. *See* Environmental management systems (EMS)  
 endurance limit, 75–76  
 energy absorption, 20  
 Energy Bill (proposed), CAFE standards, fleetwide average, 7  
 engineering stress-strain curves  
 FBDDP steel, 73(F)  
 MS steels, 129–130, 130(F)  
 TRIP steel, 73(F)  
 TRIP steels, 121, 122(T)  
 TWIP steel, 73(F)  
 environment and AHSS, 250–257(F,T)  
 automotive industry, 250  
 carbon footprint, 251, 251(F)  
 CO<sub>2</sub> emissions, reduction in, 251–252  
 crude steel production routes, 251–252  
 embodied energy chart, 253, 254(F)  
 embodied energy per unit strength, 256(F)

energy and emissions for producing aluminum, 253, 253(T)  
 energy and emissions for producing steel, 253, 253(T)  
 energy required for ore conversion and embodied energy for aluminum, 253, 253(T)  
 energy required for ore conversion and embodied energy for steel, 253, 253(T)  
 GHG emissions, 250  
 hydrogen flash smelting process, 252–253  
 index for selecting best material for a strong panel, 255–256(F)  
 Kyoto Protocol of 1997, 250  
 petroleum consumption, 250  
 steels, environmentally friendly and sustainable materials, 250–251  
 strength-embodied material property energy chart, 253–255, 254(F)  
 sustainability topics, proposed, 256(T)  
 trend for energy consumption per ton of steel, 252(F)  
 U.S. transportation sector, 250  
 environmental management systems (EMS), 249  
 Environmental Protection Agency (EPA), 6, 6(T), 7  
 EPA. *See* Environmental Protection Agency (EPA)  
 equal channel angular extrusion (ECAE) method, 64  
 equibiaxial hemispherical stretch forming, 81, 83(F)  
 European car manufacturers, flexible rolling technologies, 245–246  
 eutectoid reaction, 24  
 eutectoid steel  
 microstructure, 26, 26(F), 32, 32(F)  
 TTT diagram, 28(F)  
 extrinsic factors, 53

## F

face-centered cubic (fcc), 24, 127, 135, 151  
 fatigue, 75–77  
 cause of, 75  
 cracks, 75  
 endurance limit, 75–76  
 high-cycle fatigue, 75, 76  
 low-cycle fatigue, 75  
*S-N* curve  
 HSLA steels, 77, 77(F)  
 TRIP steels, 77, 77(F)  
 TRIP steels, 123–124

- fatigue failure, 76
- fatigue life, 76–77, 160
- ferrite
  - AHSS, 15, 18, 55
  - AHSS, microstructure design, 266–267, 267(T), 268, 268(F)
  - annealing, 38
  - AUST SS, 151
  - bainite, 27
  - carbon content, 25
  - carbon steel, 24
  - as common constituent in steels, 24
  - CP steels, 107, 109
  - definition of, 23
  - DP steels, 46, 47, 64, 73, 73(F), 95, 95(F), 98–99
  - DSTC process, 271
  - dual-phase microstructure, 100–101
  - first generation, 18
  - first generation AHSS, 60
  - galvannealed (DP) steel, 101
  - grain refinement, DP steels, 211–212, 211(T)
  - grain size, 55
  - hot rolling sheet products, 100
  - HSLA, 45
  - intercritical annealing, 64
  - iron carbide particles, 26
  - martempering, 38
  - microstructure, 41, 41(T), 43(F)
  - microstructure development, 64, 65(F)
  - MS steels, 127, 131, 132
  - nanosteels, 272
  - pearlite, 23, 26(F), 32
  - Q&P process, 269
  - quenching and tempering, 38
  - stainless steel grades, comparison, 46(T)
  - steels, 23
  - thermal processing, 40
  - thermomechanical processing, AHSS, (F), 63, 65
  - third generation AHSS, 264(T)
  - TRIP grades, 47
  - TRIP steels, 115, 116, 117, 118
  - TWIP steels, 137
  - ultrafine grains, 97, 268
- ferrite/bainite dual-phase (FBDP) steel, 72, 73(F)
- ferritic stainless steels
  - applications, 45
  - carbon content, 45
  - fundamentals, 45
  - iron, 45
- ferrous alloys, 9
- fine-grain (FG) material, 97(F), 211(T), 212, 212(F)
- finite-element analysis (FEA), 241
- flame straightening, 221
- flat rolled steel, 42, 43(T), 171–172, 172(F)
- flat-rolling process, 243(F)
- FLD. *See* forming limit diagram (FLD)
- flexible binder control unit, 238, 238(F)
- flexible binder technology, 234–235, 235(F)
- flexible binders, 236–243(F)
  - binder force profiles, 237
  - closed-loop control system, 238–239, 239(F)
  - dies, fine tuning, 236
  - flexible binder control unit, 238, 238(F), 243
  - fracture, 236
  - rigid binder with nitrogen cylinders, 236, 236(F)
  - segmented flexible binders, 239–243(F)
  - stamping industry, 236–243(F)
  - stamping trials, 242–243
  - wrinkles, 236
- flexible rolling, 243–247(F)
  - applications, 245, 246(F)
  - applications, flexible rolling blanks, 247(F)
  - ductility, 244–245
  - European car manufactures, 245–246, 247(F)
  - flat-rolling process, 243(F)
  - flow strength profiles in flexible rolled coil, 244, 245(F)
  - LDH tests, 244–245, 246(F)
  - process, 243–244
  - producing a flexible (tailor) rolled coil, 244, 244(F)
  - strain-hardening, 244
  - thickness profile, 244, 245(F)
  - United States, 246
- flow localization, 81
- formability
  - deep drawing, 83–85(F)
  - defined, 81
  - hemispherical punch forming, 81–83(F), 84(F)
  - hole expansion, 86–89(F)
  - overview, 81
  - TRIP steels, 116
  - uniaxial tension, 81
- forming dies
  - coatings, 191
  - thermal fatigue, 193
- forming guidelines, 216–217
- forming limit diagram (FLD)
  - CP steels, 112(F)
  - DP steels, 105, 105(F)
  - grids, 81, 83
  - hemispherical punch forming tests, 81, 82(F), 83

- forming limit diagram (FLD) (continued)
    - MS 1400, 84, 84(F)
    - TRIP 400/600, 84, 84(F)
  - forming load, 178
  - forming technologies
    - FSV program, 226, 226(F)
    - manufacturing processes
      - active binders, 232–235
      - active drawbeads, 230–231(F)
      - flexible binders, 236–243(F)
      - flexible rolling, 243–247(F)
      - overview, 227–228
      - real-time process control, 228–230(F)
    - stamping, 225–227(F)
    - TWB, 225–226, 226(F)
    - TWC, 225–226
  - fracture
    - flexible binders, 236
    - TWIP steels, 142
  - FSV. *See* Future Steel Vehicle (FSV)
  - fuel consumption
    - AHSS content, 162
    - aluminum versus AHSS, 258
    - effect of car weight on, 7(F)
    - effect of vehicle weight on, 9
    - greenhouse emissions, 159
    - measuring, 7
    - transportation sector, 4
  - fuel economy standards
    - cars/light trucks, 2012–2016, 6, 7(T)
    - fleet average, 7(T)
  - fuel efficiency
    - GHG emission reduction strategy, 250
    - significance of strength, 20
    - third generation AHSS, 19, 160
    - ultra-light steel family research
      - programs, 200–203(F,T), 204(F)
    - vehicle weight reduction and, 7–10(F,T)
    - weight reduction and, 20, 20(T)
  - fusion welding. *See also* individual processes
    - fusion welding processes
      - GMAW, 219
      - laser, 217
      - laser plasma, 217
      - MIG pulse/ac, 217
      - MIG pulse/dc, 217
      - MIG/laser-assisted, 217
      - resistance spot welding, 195
    - process, 195
  - Future Steel Vehicle (FSV)
    - HSS grades, new, 204(F)
    - introduction, 19
    - LCA, 259
    - program, 174–175, 200–203(F,T)
    - program results, 203(T)
    - TWBs, 226
- ## G
- gallons per mile (gpm), 7
  - galvannealed (DP) steel, 101, 101(F)
  - gas metal arc welding (GMAW)
    - ASP study (chassis structures), 219–220(F), 221(F)
    - definition of, 219
    - process, 219(F)
    - welding guidelines, 221
  - GHG emissions. *See* greenhouse gas (GHG) emissions
  - global climate change, 4
  - global projects
    - academic research and development, 205–212(F,T)
    - government/industry/academia collaboration, 203–205(F)
    - overview, 199
    - steel industry projects, 199–203(F,T), 204(F)
  - gpm. *See* gallons per mile (gpm)
  - grain boundaries
    - definition of, 55
    - nanosteels, 271–272
  - grain refinement, DP steels, 97
  - grain size
    - cold rolling, 56, 57(F)
    - ferrite, 55
    - mechanical properties, steels, 55
    - nanosteels, 272
    - strain-hardening, 97, 98(T)
  - grain-boundary/grain refinement hardening, 55, 55(F)
  - greenhouse gas (GHG) emissions
    - automotive industry, 250
    - cars/light trucks, 2012–2016, 6, 6(T)
    - sustainability, 250
    - third generation AHSS, 160
    - U.S. transportation sector, 250
  - greenhouse gases
    - carbon dioxide (CO<sub>2</sub>), 4–6, 5(F)
    - petroleum consumption, 4–5
    - vehicles, 5–6
  - grids, 81, 83
- ## H
- Hall-Petch equation, 272
  - hardening
    - AUST SS, 151
    - engineering stress-strain curves, 72, 73(F)
    - TWIP steels, 140, 148, 148(F)
  - hat-section cross member, 179, 179(F)

- heat treating (steel)
  - procedures, 37, 37(F)
  - process, 36–37
  - transformation cycles, 37–38
- heat treatment
  - description of, 26
  - isothermal heat treatment curve, 27, 29(F)
  - nanosteels, 272
  - role of, 27
  - toughness, 90
  - TRIP steels, 117, 118(F)
  - YS, 90
- heat-affected zone, 195, 197, 218, 246
- hemispherical punch forming tests, 81–83(F)
  - dome height, effect of steel strength on, 83(F)
  - FLD, 81, 82(F), 83, 84(F)
  - grids, 81, 83
  - HSLA 550 steel, LDH, 82(F)
  - LDH, 81, 82(F)
  - stretchability of various grades of steel, 83(F)
  - tooling, 81(F), 82(F)
  - TRIP 600 steel, LDH, 82(F)
- hexagonal close-packed (hcp), 53, 135, 137, 206
- high strength, significance of, 20–21(F,T)
  - cost savings, 21
  - crash performance, 20
  - energy absorption, 20
  - fuel efficiency, 20
  - mass efficiency measure, 21, 21(F)
  - material savings, 20–21
  - weight reduction, 20
  - weight reduction on yield strength, dependence of, 20(T)
- high-cycle fatigue, 75, 76
- high-strength low-alloy (HSLA) steels
  - advantages of, 45
  - alloying elements, 44, 45
  - applications, 45
  - arc welding, 196
  - carbon content, 44
  - drawbead restraining forces, 231
  - effect of cutting tool on hole expansion, 88, 88(F)
  - energy-absorption capabilities, 89, 90(F)
  - evolution of, 13
  - ferrite, 45
  - fundamentals, 44–45
  - microstructure, 45
  - S-N* curve, 77, 77(F)
  - springback, 180
  - springback profiles, 183, 183(F)
  - strain-hardening, 92, 93(F)
  - in strength-elongation space, 14, 14(F)
  - twin boundary hardening, 56
  - YS, 45
- high-strength low-alloy (HSLA) steels, types
  - HSLA 340, 218
  - HSLA 340/450, 179, 179(F), 183, 183(F)
  - HSLA 350, 183, 183(F)
  - HSLA 350/450, 74(F), 79, 79(F)
  - HSLA 350Y, 217
  - HSLA 450, 178, 178(F)
  - HSLA 550, 83(F)
- high-strength steels (HSS)
  - AISI definitions, 42, 43(T)
  - A5P document, 215–216
  - automotive industry, 9
  - costs, 16, 16(T)
  - development over time, 13, 14(F)
  - flat rolled steel delivered 2010, 16(F)
  - grade classification, 60(T)
  - IF-HS steel, 13, 14(F)
  - microstructure, 15
  - strength levels, high-strength steels, 68(F)
  - stress-strain curves, 67–68, 67(F)
  - tensile strength, 15, 15(F)
  - tensile strength versus elongation chart, 61(F), 62(F)
  - variation of percent elongation, 68(F)
- hole expansion test, 85–89(F)
  - CP 1000, 86–87(F)
  - CP 1000 SF, 87, 87(F)
  - CP steels, 112
  - DP 980, 86–87, 87(F)
  - cutting tools, 88–89, 89(F)
  - edge cracking in automotive component, 85(F)
  - edge stretchability, 85–86, 85(F)
  - effect of cutting tool on hole expansion, 88, 88(F)
  - initial blank and final expanded hole sample, 87(F)
  - initial holes, 87–88
  - process, 86
  - sheared edge stretching limits, 86, 87, 88(F)
  - stretch flangeability, determining, 86
  - stretch flanging, 85–86
  - tool set, 86, 86(F)
- hot dip coated products, 63
- hot dipped sheets, 98
- hot formed steels, 131–132
- hot forming, 192–193(F)
  - dimensional accuracy, 192
  - drawbacks, 192–193
  - plastic deformation, 192

hot forming (continued)  
 process, 192, 192(F)  
 quenching, 192  
 springback, 192  
 total elongation, 192

hot rolled products, 45, 63, 64, 98

hot rolling  
 carbon steels, 56, 57(F)  
 DP steels, 100, 100(F)  
 MS steels, 128  
 TWIP steels, 139

HSLA. *See* high-strength low-alloy (HSLA) steels

HSS. *See* high-strength steels (HSS)

hydraulic press cushion, 184

hydrogen flash smelting process, 252–253

**I**

ICME. *See* Integrated Computational Materials Engineering (ICME)

IF steel. *See* interstitial-free (IF) steel

IF-HS steel. *See* interstitial-free, high-strength (IF-HS) steel

IISI. *See* International Iron and Steel Institute (IISI)

Improved Materials and Powertrain Architecture for 21st Century Trucks (IMPACT) project, 170

Integrated Computational Materials Engineering (ICME), 273–274

intercritical annealing  
 carbon, 63  
 DP steels, 98, 99(F)  
 ferrite, 64  
 process, 64  
 thermomechanical processing, 63  
 TRIP steels, 118, 124

intercritical temperature, 63, 63(F), 99, 100

intergranular corrosion, 197

International Iron and Steel Institute (IISI), 258, 258(T)

International Organization of Motor Vehicles (OICA), 2–3

International Ultra-Light Steel Auto Body (ULSAB)  
 classes of steel, definitions, 42, 43(T)  
 UTS, defined, 42  
 YS, defined, 42

interstitial atoms, 54

interstitial-free (IF) steel  
 energy-absorption capabilities, 89, 90(F)  
 springback, 183, 183(F)  
 in strength-elongation space, 13, 14(F)

interstitial-free, high-strength (IF-HS) steel, 13, 14(F), 18(F), 49(T)

intrinsic factors, 53

iron  
 atoms, 33  
 AUST SS, 45, 151  
 BOF, 251–252  
 carbon, 253  
 composition and metallurgical phases, 23  
 duplex (ferritic-austenitic) stainless steels, 46  
 embodied energies, 253  
 $\text{Fe}_3\text{C}$  precipitates, 33  
 Fe-C phase diagram, 24  
 ferrite, 25  
 ferritic stainless steels, 45  
 hydrogen flash smelting process, 252  
 iron ore, 259  
 iron-carbon phase diagram, 25  
 martensite, 132  
 martensitic transformation, 33  
 MS steels, 45  
 ore to steel, 20, 251  
 recycling, 259  
 TRIP steels, 115  
 TWIP grades, 48

iron carbide ( $\text{Fe}_3\text{C}$ ), 25(F), 26, 26(F), 27, 269. *See also* cementite (iron carbide  $\text{Fe}_3\text{C}$ )

iron-phase diagram, 25

IS steel. *See* isotropic (IS) steel

isothermal annealing, 118

isothermal cooling (TTT) diagram, 30(F), 31(F)

isothermal heat treatment curve, 27, 28(F)

isothermal hold, 64, 118

isotropic (IS) steel, 13, 14(F)

**J**

joining, 220–221

**K**

knee, the  
 avoiding, 34, 35  
 bainite formation, 27  
 martensite, 32  
 pearlite formation, 27

knee of the curve, 27, 29(F)

Kyoto Protocol of 1997, 250

**L**

laser plasma welding, 217

laser welding, 217

- LCA. *See* life cycle assessment (LCA)
- LDC. *See* lightweight design coefficient (LDC)
- LDH. *See* limiting dome height (LDH)
- LDR. *See* limiting drawing ratio (LDR)
- life cycle assessment (LCA), 257–259(F,T)
- aluminum, switching from low-carbon steel, 258–259
  - aluminum to low-carbon steel, switching from, 258–259
  - automobiles, 257
  - CO<sub>2</sub> equivalents, saving, 259
  - embodied energy for aluminum, 258, 258(T)
  - embodied energy for steel, 258, 258(T)
  - energy demands, typical vehicle, 257–258, 258(F)
  - FSV program, 259
  - life cycle greenhouse gas emissions, typical car, 257, 257(T)
- light vehicle total weight
- 2010 light vehicle, 1
  - material share of finished curb weight trends, 171(F)
- light vehicles
- AHSS content (North America 2006), 173(F)
  - AHSS content (North America 2006–2012), 160(F)
  - AHSS content, projections, 200
  - carbon footprint, 6(T)
  - flat rolled steel (2010), 16
  - flat rolled steel content (2010), 17(F)
  - historical and projected AHSS content, 174(F)
  - material share percent of finished curb weight, 171(F)
  - shift from high-density and moderate-strength materials, 171
- lightweight design coefficient (LDC), 21, 21(F)
- lightweight materials
- AHSS, 10
  - aluminum alloys, 11–12
  - cost benefit analysis, 10
  - cost penalties for reducing mass, 10, 11(F)
  - cost summary of ULSAB, 11, 11(T)
  - examples, 9
  - fuel efficiency, 9
  - HSS, 10
  - life-cycle cost, 10
  - product cost, 10
  - specific strength of, 12(F)
  - structural performance, 10
  - weight savings and costs, 10, 10(T)
- lightweighting, 9, 193
- limestone, 252, 259
- limiting dome height (LDH)
- DP 750, 156(F)
  - SS 900, 156(F)
  - AUST SS, 155–156, 156(F)
  - hemispherical punch forming tests, 81, 82(F)
- limiting drawing ratio (LDR), 85, 85(F)
- liquid zinc, 197
- liquid zinc embrittlement, 197
- loading, modes of, 39
- lock beads, 187–188
- low alloy steels
- AISI/SAE composition ranges, 44(T)
  - AISI/SAE designation systems, 44(T)
- low-carbon steel
- alloy content in one type of advanced high-strength steel, 261(T)
  - alloy content in one type of low-carbon steel, 261(T)
  - aluminum, versus, 258–259, 258(T)
  - carbon content, 44
  - coefficient of expansion, 197
  - dual-phase (DP) grades, 47
  - heat treatment, 96
  - resistance welding performance study, 219
- low-cycle fatigue, 75
- lower yield strength (LYS), 92(F)
- ## M
- magnesium alloys
- ductility, 12, 13(F)
  - fuel efficiency, improving, 9
  - yield strength, 12, 13(F)
- magnetic separation, 260
- manganese
- alloy steels, 44
  - AUST SS, 45, 48, 152
  - austenite, 24
  - HSLA, 44, 45
  - MS grades, 48
  - MS steels, 128
  - second generation AHSS, 61
  - stainless steels, 45
  - TWIP grades, 48
  - TWIP steels, 135, 137, 145(T)
- martempering
- conventional, 38
  - ferrite, 38
  - TTT diagram, 37, 37(F)
- martensite
- conventional quenching/tampering, 38
  - definition of, 23
  - DP grades, 47
  - ductility, 33
  - formation from austenite, 34, 35(F)

- martensite (continued)
    - importance of, 32, 128
    - iron, 132
    - microstructure, 33(F)
    - microstructure, effect of cooling rate on, 34(F)
    - production of, 127 (*see also* martensitic stainless (MS) steels)
    - properties, temperature effects on, 32
    - softening, 32, 128
    - strengthening mechanism, 34
    - tampering, 33, 34, 35(F)
    - tempered, 127
    - tempered martensite, properties, 128
    - tempering, 132, 132(F)
    - transformation, 33
    - transformation to, 32
    - yield stress, 132, 132(F)
    - YS, 132
  - martensite islands, 95–96, 95(F), 98, 99, 101
  - martensitic (MS) grades
    - alloying elements, 48
    - carbon content, 48
    - fundamentals, 48
    - tampering, 48
    - UTS, 48
  - martensitic (MS) steels. *See also*
    - martensite
    - alloying elements, 128
    - applications, 133
    - atoms, 127
    - attributes, 133
    - carbon, 45, 48
    - carbon content, 128
    - compositions, 127–128
    - deformation mechanism, 128–129
    - ferrite, 127, 131, 132
    - hot formed steels, 131–132
    - hot forming, 130–132(F)
    - iron, 45
    - martensite, 128
    - mechanical properties, 129–130(F,T)
      - downgaging, 129
      - ductility, 129
      - engineering stress-strain curves, 129–130, 130(F)
      - mechanical properties, 129, 129(T)
      - tensile strength, 130
      - tensile strength range, 129
      - tensile strength-total elongation space, 129, 129(F)
      - true stress-strain curves, 129–130, 130(F)
      - YS, 130
    - microstructures, 127–128, 128(F)
    - overview, 127
    - postquench tempering, 127–128
    - processing of, 128
    - quenching, 131
    - in strength-elongation space, 14, 14(F)
    - tensile strength-total elongation space, 129, 129(F)
    - thermomechanical processing, 64
    - total elongation, 129, 129(T)
    - welding, 196, 197
  - martensitic stainless (MS) steels
    - applications, 45
    - carbon content, 45
    - fundamentals, 45
  - martensitic transformation, 33, 52, 127, 137, 141
  - mass efficiency measure, 21, 21(F)
  - mechanical twins
    - Fe-30Mn steel, 207, 207(F), 209(F)
    - manganese, 137
    - plastic deformation, 51, 56, 135
    - SFE, 51, 136
    - TRIP steels, 118
    - TWIP grades, 48
    - TWIP steels, 137, 140, 141–143, 142(F)
  - mechanical working. *See* strain-hardening
  - microalloying, 45
  - MIG pulse/ac welding, 217
  - MIG pulse/dc welding, 217
  - MIG/laser-assisted welding, 217
  - mild (MILD) steel
    - MS 1300, 218
    - MS 1400, 84(F)
    - arc welding, 196
    - drawbead restraining forces, 231
    - press energy, 179, 179(F), 180
    - springback, 180
    - in strength-elongation space, 13, 14(F)
    - tensile strength versus elongation chart, 61(F), 62(F)
    - twin boundary hardening, 56
  - MILD steels. *See* mild (MILD) steel
  - miles per gallon (mpg), 7
  - modulus of elasticity, 71, 222, 222(T)
  - molybdenum
    - alloy steels, 44
    - AUST SS, 151
    - HSLA, 44
    - MS grades, 48
    - MS steels, 128
    - stainless steels, 45
  - mpg. *See* miles per gallon (mpg)
  - MS grades. *See* martensitic (MS) grades
  - MS steels. *See* martensitic (MS) steels
  - multi-point cushion systems, 234–235
- ## N
- nanosteels, 272, 273
    - atoms, 271
    - bulk nanomaterials, 272



- crystalline nanomaterials, 271–272
  - defined, 271
  - ferrite, 272
  - Ford Motor Company, 273
  - General Motors, 273
  - grain boundaries, 271–272
  - grain size, 272
  - Hall-Petch equation, 272
  - heat treatment, 272
  - NanoSteel Company, Inc., 272–273, 273(F)
  - nanostructured, cold formable sheet AHSS, 272
  - properties, 271
  - strength-elongation performances, 272
  - National Highway Traffic Safety Administration (NHTSA), 6, 6(T)
    - fuel/emission requirements, model years 2017–2025, 7
  - National Institute of Standards and Technology (NIST), 204
  - National Science Foundation (NSF), 205, 256, 265–266
  - necking
    - AUST SS, 155
    - TWIP steels, 142
  - next-generation tactical vehicle, 170
  - NHTSA. *See* National Highway Traffic Safety Administration (NHTSA)
  - nickel
    - alloy steels, 44
    - AUST SS, 45, 48, 151, 152
    - austenite, 24
    - duplex (ferritic-austenitic) stainless steels, 46
    - HSLA, 44, 45
    - MS grades, 48
    - MS steels, 128
    - precipitation-hardening stainless steels, 46
    - second generation AHSS, 61
    - stainless steels, 45
    - TRIP steels, 115
  - niobium
    - AUST SS, 151
    - CP grades, 47
    - CP steels, 107, 108
  - NIST. *See* National Institute of Standards and Technology (NIST)
  - nitriding, 190
  - nitriding plus physical vapor deposition, 191
  - nitrogen
    - AUST SS, 45, 48
    - bake hardening, 91
    - stainless steels, 45
  - nitrogen cushions, 232
  - nitrogen cylinders, 184, 236, 236(F)
  - nonautomotive applications, 169–171(F)
    - applications, 170(F)
    - IMPACT project, 170
    - improve performance/reduce costs, examples, 170(F)
    - next-generation tactical vehicle, 170
    - steel packaging, 170–171
  - nonferrous alloys, 9
  - nonmetallic lightweight materials, 9
  - normalizing, 37
  - North America
    - flat rolled steel delivered (2010), 16–17, 17(F)
    - projected light vehicle production, 2–3, 3(F)
    - world auto production, 2–3
  - North American light vehicles
    - downgaging limits, 194
    - weight, 2010, 194
  - NSF. *See* National Science Foundation (NSF)
- ## O
- OEMs. *See* original equipment manufacturers (OEMs)
  - OHF. *See* open hearth furnace (OHF)
  - open hearth furnace (OHF), 251, 252
  - original equipment manufacturers (OEMs)
    - categorization scheme, flat rolled steels, 42
    - segmentation of flat rolled steel grades, 43(T)
- ## P
- packaging steels, 170–171
  - PACVD. *See* plasma-assisted chemical vapor deposition (PACVD)
  - paraequilibrium, 269
  - partitioning, 269. *See also* quenching and partitioning (Q&P) process
    - carbon partitioning, 270, 270(F)
    - DSTC process, 270
    - novel processing methods, 268
    - third generation AHSS, 263
  - Partnership for New Generation of Vehicles (PNGV), 204
  - pearlite
    - definition of, 23
    - eutectoid steel, microstructures resulting from fast and slow CCR, 30, 31(F), 32
    - ferrite, 26(F), 32
    - isothermal transformation of eutectoid steel from austenite to pearlite, 27–28, 29(F)
  - knee, the, 27

petroleum  
 CO<sub>2</sub> emissions, from gallon of fuel, 6, 6(T)  
 U.S. petroleum production/consumption (all sectors) 1973-2035, 3-4, 3(F)  
 U.S. petroleum production/consumption (transportation sector) 1973-2035, 4, 4(F)  
 world demand, 3-4  
 phase transformations, 53, 55-56  
 phosphorus, 44, 45  
 physical vapor deposition (PVD), 191  
 plain carbon steel  
 AISI/SAE composition ranges, 44(T)  
 AISI/SAE designation systems, 44(T)  
 carbon content, effect on mechanical properties, 39(F)  
 ductility, 39  
 effect of microstructure on mechanical properties, 40(F)  
 plasma-assisted chemical vapor deposition (PACVD), 191  
 plastic deformation, 51, 53, 192  
 plastic flow, 38  
 plastic strain, 72-73, 83, 210, 211(F)  
 plastic zone, 89-90  
 postquench tempering, 128  
 post-stretch process, 187  
 precipitation hardening  
 AHSS, 18  
 overview, 54  
 stainless steels, 46, 46(T)  
 press load, 179, 179(F)  
 press requirements, 177-180  
 DP 600, 178, 178(F)  
 flow stress, 178  
 forming load, 178  
 hat-section cross member, 179, 179(F)  
 HSLA 450, 178, 178(F)  
 load and energy required for forming, 178, 178(F)  
 press energy, 179-180, 179(F)  
 press load, 179, 179(F)  
 thickness reduction, 178-179  
 uniaxial tensile testing, 177-178  
 pressure cushions. *See* active binders  
 pre-strain (PS), 92(F)  
 programmable binders. *See* active binders  
 progressive crush zones, 78-79  
 PVD. *See* physical vapor deposition (PVD)

## Q

quench hardening, 55-56  
 quench hardening (phase transformation), 55-56

quenching  
 austenite to martensite, 34, 35(F)  
 conventional, 38  
 DP steels, 96, 98  
 ferrite, 38  
 hot forming, 192  
 MS steels, 128, 131  
 plain carbon steel, 40, 42(F)  
 TWIP steels, 139  
 quenching and partitioning (Q&P) process, 269-270, 270(F)

## R

real-time process control, 228-230  
 binder force trajectory, 228  
 closed-loop system, 228, 229-230, 230(F)  
 feedback process control, 229, 229(F)  
 successful and failed cups, 229, 229(F)  
 tearing, 228  
 wrinkling, 228, 229-230  
 recovery, 57  
 recovery annealed steel, RA 830, 218  
 recrystallization, 57  
 recycling, 259-261(F,T)  
 alloy content in one type of advanced high-strength steel and low-carbon steel, 261(T)  
 carbon content, 260-261  
 iron ore, 259  
 life cycle of steel, 259-260, 260(F)  
 magnetic separation, 260  
 steel, recycled annually, 259  
 steel recycling rate, 260  
 vehicles, 260  
 residual stress, 186-187. *See also* springback  
 resistance spot welding  
 automotive industry, 195  
 components, 195(F)  
 process, 195, 195(F)  
 process conditions, 196(F)  
 welding guidelines, 195-196  
 welding schedules, modifications to, 221  
 resistance welding performance study, 218-219, 218(F)  
 room-temperature dynamic strain aging, 146-147  
 rules of mixtures, 266

## S

safety zone, 78, 78(F), 79  
 scanning electron microscope (SEM)  
 Fe-24Mn, 208(F)

- Fe-28Mn, 210
- Fe-30Mn, 207(F)
- grain sizes, DP steels, 97, 97(F)
- second moment of inertia, 193
- segmented flexible binders, 239–243(F)
  - closed-loop flexible binder control system, 239–242(F)
    - binder force trajectories, 241–242, 242(F)
    - FEA simulation, 241
    - liftgate die mounted in mechanical press, 240(F)
    - liftgate inners, 241, 241(F)
    - segmented lower die for liftgate panel, 240(F)
    - splits, 241
    - wrinkling, 241
  - USCAR program, 239–242(F)
- selenium, 44
- sensitization, 197
- shape-set process, 187
- sheet metal
  - corrugation, 72, 194
  - deep drawing, 83–85(F)
  - dimpling, 72, 194
- sheet metal forming. *See also* real-time process control
  - active drawbeads, 230–231
  - component thinning, 81
  - deep drawing, 83–85(F)
  - flow localization, 81
  - grid deformation, 83
  - springback, 180
  - strain distribution, 230
  - system, 187, 188(F)
- sheet metal forming system, 188, 188(F)
- sidewall curl, 180, 183(F), 184
- silicon
  - alloy steels, 44
  - AUST SS, 151
  - DSTC process, 271
  - HSLA, 44, 45
  - MS grades, 48
  - MS steels, 128
  - TRIP steels, 115, 117
  - TWIP steels, 135
- slip
  - AUST SS, 153
  - deformation by dislocation glide, 51
  - grain boundary/grain refinement hardening, 55, 55(F)
  - mechanical working, 54–55
  - nanosteels, 272
  - SFE, 141
  - solid-solution strengthening, 54
  - strengthening mechanisms, 53
  - twinning, 136
  - twins, 136
  - TWIP steels, 210
  - slip plane, 51, 51(F), 54, 55, 136
  - slip systems, 53, 136, 153
- SMDI. *See* Steel Market Development Institute (SMDI)
- S-N* curves
  - CP steels, 110, 111(F)
  - DP steels, 104, 104(F)
  - fatigue, 75
  - fatigue characteristics, 76(F)
  - HSLA steels, 77(F)
  - TRIP steels, 77(F)
- solid-solution hardening, 72, 135, 137
- solid-solution strengthening (alloying), 18, 45, 54
- solid-state diffusion, 26
- solute atoms, 54
- splits, 216, 236, 241
- spot weld, 218, 218(F)
- springback
  - active binders, 232, 234
  - AKDQ steels, 180
  - allowance, 180
  - bending forces, 184
  - binder force profile in a shape-set process, 187, 187(F)
  - body panels, 185
  - computer simulation, 186
  - curl radius, 184, 185(F)
  - drawbead penetration, 184, 184(F)
  - drawing component, 180
  - elastic recovery, 180–181, 181(F)
  - explained, 180–181
  - formed U-channel, 180, 181(F)
  - hot forming, 192
  - HSLA, 180
  - IF steel, 183, 183(F)
  - magnitude of, 186
  - metal flow, controlling, 184
  - MS steels, 182(F)
  - overview, 180
  - post-stretch process, 187
  - profiles, 183, 183(F)
  - punch radii, 184
  - punch radius, 184, 184(F)
  - reducing, 184, 187
  - removing, 180
  - shape-set process, 187
  - stamped components, 185
  - Standard Test Method for Evaluating Springback of Sheet Metal Using the Demeri Split Ring Test, 186–187, 186(F)
  - stretch forming, 180
  - U-channel forming, 182–183(F)
  - variable binder force control, 184–185
  - YS, effect on, 181–182, 182(F)
- springback allowance, 180

- stacking fault energy (SFE)
  - Fe-22Mn-0.6C steel, 52
  - fundamentals, 51–52
  - overview, 136
  - TRIP effect, 52, 140, 141
  - TWIP effect, 52, 140
  - TWIP steels, 135, 137, 140
- stacking fault (SF), 51
- stacking faults, 136
- stainless steels, 46, 46(T)
  - alloying elements, 45
  - austenitic stainless steel (*see* austenitic stainless steels (AUST SS))
  - carbon content, 45
  - chromium, 45
  - duplex (ferritic-austenitic) stainless steels (*see* duplex (ferritic-austenitic) stainless steels)
  - ferritic stainless steels (*see* ferritic stainless steels)
  - fundamentals, 45–46
  - martensitic stainless (MS) steels (*see* martensitic stainless (MS) steels)
  - precipitation-hardening, 46, 46(T)
  - properties, 45
  - relative properties, comparison of, 46(T)
  - SS301LN, 67–68, 68(F)
- stamped components
  - real-time process control, 228
  - springback, 185
- stamping, 225–227(F)
  - binders, 227
  - flexible binders, 236–243(F)
  - multi-point cushion systems, 235
  - tooling, 227, 227(F)
- Standard Test Method for Evaluating Springback of Sheet Metal Using the Demeri Split Ring Test, 186–187, 186(F)
- steel fundamentals
  - annealing, 57, 57(F)
  - categories (*see* steels, categories)
  - compositions and metallurgical phases, 23–25(F)
  - deformation mechanisms, 50–53(F)
  - deformation processing, 56–57, 57(F)
  - microstructure and heat treatment, 25–38(F,T)
  - overview, 23
  - strengthening mechanisms, 53–56(F)
  - structure-property relationships, 38–41(F,T), 42(F), 43(F)
- steel industry projects, 199–203(F,T)
  - AISI, 199–200
  - ASP, 199
  - FSV, 200–203, 201(F), 202(F), 203(T), 204(F)
  - light vehicle programs/results, 203(T)
- SMDI, 199–200, 203
- ULSAB, 200
- ULSAB-AVC, 200, 203, 204(F)
- ULSAC, 200
- ULSAS, 200
- ultra-light steel family research programs, 200, 201(F)
- WAS, 199, 200, 203
- Steel Market Development Institute (SMDI), 199–200, 203, 205, 273
- steels. *See also* individual types
  - advanced (*see* advanced steels)
  - advantages of, 1
  - AHSS (*see* advanced high-strength steel (AHSS))
  - alloy editions, 41–42
  - versus aluminum alloys (cost advantage), 11–12
  - applications, 23
  - austenitizing, 38
  - automotive industry, 13–15, 14(F)
  - BH steel (*see* bake-hardenable (BH) steels)
  - carbon content, 23
  - cooling rates, effect on microstructure, 35(F)
  - cost advantage, 15–16, 16(T)
  - dependence of the eutectoid temperature on alloy concentration, 25(F)
  - ductility, 12, 13(F)
  - elongation-strength-hardness chart, 50(F)
  - embodied energy, 258, 258(T)
  - endurance limits, 76
  - energy and emissions for producing, 253, 253(T)
  - energy required for ore conversion and embodied energy, 253, 253(T)
  - evolution of, 13
  - ferrite, 23
  - forming limit diagrams, comparison of, 69, 70(F)
  - grades in automobiles, 13
  - heat treating, 36–38(F)
  - heat treatment, 27–30(F)
  - HSLA (*see* high-strength low-alloy (HSLA) steels)
  - HSS (*see* high-strength steels (HSS))
  - HSS development over time, 13, 14(F)
  - IF steel (*see* interstitial-free (IF) steel)
  - importance of, 12–17(F,T)
  - iron, 23
  - IS steel (*see* isotropic (IS) steel)
  - light vehicle total weight (2010), 13
  - low-alloy and high-alloy, boundary between, 41
  - mechanical properties, determining, 64

- mechanical/performance properties, determining, 38–39
- microstructural effects on mechanical properties, 41(T)
- microstructural features, 27
- microstructure, effect on strength, 39, 39(T)
- microstructures of various phases of steel grades, 43(F)
- MILD steel (*see* mild (MILD) steel)
- modes of loading, 39
- North American shipments 2010, 16(F)
- production 2011, 13
- recycling rate, 260
- steel grade selection, 14(F), 15
- versatility of, 1
- yield strength, 12, 13(F)
- steels, categories, 41–50(F,T)
  - AISI and ULASAB definitions, 43(T)
  - AISI/SAE and UNS designation systems and composition ranges, 44(T)
  - alloy steel (*see* alloy steels)
  - alloying elements, 41–42
  - automotive industry, 49–50, 49(T)
  - BH steel (*see* bake-hardenable (BH) steels)
  - carbon steels (*see* carbon steels)
  - definitions of, 42
  - ductility-strength-hardness chart, 50(F)
  - elongation-strength-hardness chart, 49–50, 50(F)
  - groups in each category, 49(T)
  - HSLA (*see* high-strength low-alloy (HSLA) steels)
  - segmentation of flat rolled steel grades by OEMs, 43(T)
  - stainless steels (*see* stainless steels)
  - strength-elongation relationships, 49(F)
  - tensile strength ranges, 49(T)
- stiffness
  - automotive applications, 160
  - bending stiffness, 222(T)
  - buckling stiffness, 222(T)
  - corrugation, 72
  - defined, 71, 193
  - dimpling, 72
  - downgaging, 177, 193
  - downgaging limits, 193–194
  - increasing, 194
  - measured by, 71
  - modulus of elasticity, 71
  - performance evaluation, 222, 222(T)
  - sheet metal, 72
  - specific stiffness, 222
  - steels, 193–194
  - torsional stiffness, 21
- strain-hardening, 72–75(F)
  - AHSS, 46, 59, 72–75(F)
  - AUST SS, 154, 156
  - crash performance, 20
  - DP steels, 47, 73, 92, 93(F), 97, 102
  - energy absorption, 20
  - flexible rolling, 244
  - grain size, 97, 98(T)
  - HSLA steels, 92, 93(F)
  - instantaneous n-values for different steel grades, 74(F)
  - strain-hardening exponent, 72–73, 74(F)
  - strengthening mechanisms, 54
  - TRIP grades, 47
  - TRIP steels, 73, 92, 93(F), 115–116, 120, 121(T), 123
  - TWIP steels, 135, 140, 141(F), 142
- strength
  - AHSS, 72
  - defined, 72
  - dislocation glide, 72
  - engineering stress-strain curves, FDBP, TRIP, TWIP, 72, 73(F)
  - lattice imperfections, 72
  - measuring, 72
  - plastic strain, 72
  - significance of (*see* high strength, significance of)
  - UTS, 72 (*see also* ultimate tensile strength (UTS))
  - YS, defined, 72 (*see also* yield strength (YS))
- strengthening mechanisms, 52–53. *See also* alloying
  - dispersion hardening, 54
  - fundamentals, 53
  - grain-boundary/grain refinement hardening, 55, 55(F)
  - mechanical working (strain hardening), 54 (*see also* strain-hardening)
  - precipitation hardening, 54
  - quench hardening (phase transformation), 55–56
  - solid-solution strengthening (alloying), 54, 54(F)
  - twin boundary hardening, 56, 56(F)
- strength-to-weight ratios, 9, 45, 193
- stress cracking, 187
- stress-corrosion cracking, 46, 187
- stress-relieving, 37, 44
- stretch forming, 180
- Structure and Mechanical Properties of Fe-Mn Alloys, 205–210(F,T)
  - chemical compositions of high-manganese steels, 206(T)
  - Fe-24Mn alloy, summary of results, 207–210(F)
  - Fe-30Mn alloy, summary of results, 206–207(F,T), 208(F)
  - overview, 205–206

structure-property relationships, 38–41(F,T), 42(F), 43(F)  
 substitutional atoms, 54  
 sulfur, 44, 45  
 sustainability, 249–250(F)  
   CO<sub>2</sub> emissions, 250  
   CO<sub>2</sub> footprint, 250  
   embodied energy, 250  
   greenhouse gas emissions, 250  
   life cycle emissions, vehicle, 250, 250(F)  
   materials, 249  
   World Steel Association, 249–250

## T

tailor welded blanks (TWB)  
   automotive applications, 225–226  
   benefits of, 225  
   defined, 225  
   FSV program, 201, 226, 226(F)  
   hot formed, 202(F)  
   ULSAB program, 226  
 tailor welded coils (TWC), 225  
 tempered martensite  
   attributes, 35(T)  
   heat treatment, 127  
   microstructure, 35(T), 38  
   properties, 32, 128  
   strengthening mechanism, 34, 128–129, 132  
 tempering  
   conventional, 38  
   DP steels, 96  
   ferrite, 38  
   martensite, 33, 34, 35(F), 132, 132(F)  
   MS grades, 48  
   MS steels, 127  
   plain carbon steel, 40–41, 42(F)  
   postquench tempering, 127–128  
   TTT diagram, 37, 37(F)  
   welding, 196  
 tensile strength  
   AHSS, 59, 66, 66(F)  
   AHSS generations, 60(T), 61(F,T), 62(F)  
   AUST SS, 48, 153  
   carbon steel, 40–41, 41(F)  
   CP steels, 109, 109(F)  
   DP steels, 102(F)  
   HSS, 15, 15(F), 61(F), 62(F)  
   mild (MILD) steel, 61(F)  
   MILD steel, 62(F)  
   MS steels, 129, 129(F), 130, 131, 131(F)  
   steels, categories, 49(T)  
   structure-property relationships, 38  
   TRIP grades, 47  
   TRIP steels, 120, 121(F)  
   TWIP steels, 18, 142, 143, 143(F)  
 tensile strengths  
   CP grades, 47  
   DP grades, 47  
 tensile strength-total elongation space  
   CP steels, 109, 109(F)  
   DP steels, 102, 102(F)  
   MS steels, 129, 129(F)  
   TRIP steels, 120, 121(F)  
   TWIP steels, 143, 143(F)  
 thermal diffusion (TD), 191  
 thermal processing, 26, 45  
 thermomechanical processing, 211  
   advanced steels, 17  
   annealing, 63  
   bainite isothermal transformation  
   treatment, 64  
   continuously annealed products, 63  
   CP steels, 64  
   DP steels, 64  
   heat treatment, 63  
   hot dip coated products, 63  
   hot-rolled products, 63  
   intercritical annealing, 63, 64  
   MS steels, 64  
   processing schemes, AHSS grades, 64  
   TRIP steels, 64  
   ultrafine-grained alloy, 64  
 thickness reduction, 178–179  
 third generation AHSS, 263–266(F,T)  
   automotive industry availability target, 265, 265(F)  
   computer modeling, 268  
   cost problem, 265  
   ductility, 62  
   expected location in strength-ductility space, 263–264, 264(F)  
   ferrite, 264(T)  
   fuel efficiency, 19, 160  
   fuel efficiency, improving, 160  
   greenhouse gas emissions, 160  
   key requirements, 264  
   manufacturing processes, 265  
   microstructural classes of conventional high-strength steels (HSS), 264(T)  
   microstructure design, 266–268(F,T)  
   basis of, 266  
   composite model for strength, 267(F)  
   mechanical properties, 268  
   rules of mixtures, 266  
   strength-ductility relationships, 266–267, 267(F)  
   strength-ductility relationships for microstructure constituents, 267(T)  
   superposition of predicted microstructure design on strength-ductility plot, 268(F)

- novel processing methods (*see* third generation processing methods)
- partitioning, 263
- research underway, 264–265
- strength, 62
- strength-ductility space, location of, 61–62, 62(F)
- structural mass reduction, 160
- vehicle body structure mass, reduction in, 19
- work-hardening, 268
- third generation processing methods, 268–271(F)
  - composite modeling, 271
  - DSTC process, 270–271, 271(F)
  - overview, 268
  - Q&P process, 269–270, 270(F)
- time-temperature-transformation (TTT) diagram, 27, 64
- titanium
  - AUST SS, 151
  - CP grades, 47
  - CP steels, 107, 108
  - HSLA, 45
  - stainless steels, 45
  - TRIP steels, 115
- titanium alloys, 9
- titanium carbide (TiC), 191
- titanium carbonitride (TiCN), 191
- titanium nitride (TiN), 191
- tonnage
  - AHSS, 184
  - flexible binders, 237
  - forming guidelines, 216
  - forming operation, 178
  - HSS, 184
  - incorrect estimation, consequences of, 180
  - metal flow, controlling, 184
  - splits, 241
  - U-channel forming, 233
- tool material and die wear, 189–192(F)
  - cause of, 189–190
  - coatings, 190–192, 191(F)
  - nitriding, 190–191
  - preventing, 190
  - surface treatment (tool wear), 190–191, 190(F)
  - tool life, 191, 191(F)
  - vanadium carbide, 191
- total elongation
  - AHSS grades, 154(T)
  - CP steels, 109, 109(T)
  - DP steels, 97, 98(T), 102, 103(T), 211(T), 212(F)
  - Fe-24Mn steel, 146(F)
  - formability, 81
  - grain size, 55
  - hot forming, 192
  - mechanical properties for various grades of steels, 66(T)
  - MS steels, 129, 129(T)
  - TRIP steels, 67, 120, 121(F,T), 144(T)
  - TWIP steels, 72, 143, 145, 145(F,T)
  - uniaxial tension, 81
- total elongation range, 99
- toughness
  - AUST SS, 154–155
  - automotive steels, energy-absorption capabilities of, 89, 90(F)
  - cracks, 89
  - defined, 38, 89
  - first generation AHSS, 90
  - heat treatment, 90
  - increasing, 90
  - measure of, 89
  - measuring, 38
  - plastic zone, 89–90
  - second generation AHSS, 90
  - variation of fracture toughness with yield strength, 90, 90(F)
  - YS, 89–90, 90(F)
- traditional stamping
  - binder force, 188
  - restraining force, 188–189
- transformation-induced plasticity, 115
- transformation-induced plasticity (TRIP) grades
  - applications, 47–48
  - ferrite, 47
  - formability, 47
  - fundamentals, 47–48
  - martensitic formation, 47–48
  - phases, 47
  - strain-hardening, 47
  - strain-hardening rate, 47
  - tensile strength, 47
- transformation-induced plasticity (TRIP) steels
  - advantages of, 123
  - applications, 115, 123
  - attributes, 123–124
  - bake hardening, 92–93, 92(F)
  - carbon, 116–117, 119
  - composition and microstructure, 115–117(F,T)
  - alloying elements, 115
  - applications, 116
  - carbon content, 116–117
  - characterizations of, 115–116
  - chemical compositions, 116, 117(T)
  - microstructure, 116
  - microstructure, schematic, 117(F)
  - phases, 115
  - TRIP 700, chemical composition, 117(T)

- transformation-induced plasticity (TRIP) steels (continued)
  - costs versus HSS, 124
  - CR TRIP steel, 121, 121(T)
  - crashworthiness, 80
  - deformation mechanism, 119, 119–120(F)
  - energy-absorption capabilities, 89, 90(F)
  - engineering stress-strain curve, 72, 73(F)
  - fatigue properties, 123
  - ferrite, 115, 116, 117, 118
  - FLD, 123, 124(F)
  - formability, 123
  - intercritical annealing, 124
  - iron, 115
  - mechanical properties, 120–123(F,T)
    - coatings, 121, 121(T)
    - CR TRIP steel, 121, 121(T)
    - energy absorption properties, 122–123
    - engineering stress-strain curves, 121, 122(T)
    - formability, 121
    - mechanical properties, 121(T)
    - microstructure, phases, 121–122
    - tensile strength range, 120
    - tensile strength-total elongation space, 120, 121(F)
    - total elongation range, 120
    - toughness, 122–123
    - TRIP 590, 121, 121(T)
    - TRIP 780, 121, 121(T)
    - TRIP effect, 123
    - true stress-strain curves, 121, 122(T)
    - work hardening rate, 121, 122
  - overview, 115
  - processing of, 117–119(F)
    - cold rolling, 117, 118(F)
    - cooling schedule, TRIP sheet, 118(F)
    - heat treatment, 117, 118(F)
    - hot rolled TRIP steel, 118–119, 119(F)
    - time-temperature schedule, hot rolled DP steels, 119(F)
    - time-temperature schedule, hot rolled TRIP, 119(F)
  - S-N* curve, 77, 77(F)
  - strain-hardening, 92, 93(F), 115–116, 120, 121(T), 123
  - strain-hardening rate, 73
  - in strength-elongation space, 14, 14(F)
  - tensile strength-total elongation space, 120, 121(F)
  - thermomechanical processing, 64
  - total elongation, 120, 121(F,T)
  - transformation-induced plasticity, 115
  - TRIP effect, 120, 120(F)
  - TWB, 226
  - welding, 196–197
  - work-hardening, 67, 119, 121–122, 206
- transformation-induced plasticity (TRIP) steels, types
  - CR TRIP steel, 121, 121(T)
  - TRIP 350/600, 73–75, 74(F)
  - TRIP 400/600, 83, 84(F)
  - TRIP 590, 121, 121(T)
  - TRIP 600, 83(F), 196, 218
  - TRIP 690, 124(F)
  - TRIP 700, 117(T), 154(F), 183
  - TRIP 780, 121, 121(T), 124(F), 196
  - TRIP 800, 218
- transmission electron microscopy (TEM), 50, 52
- Transportation Energy Data Book, 3
- transportation sector
  - carbon dioxide (CO<sub>2</sub>), 5–6
  - petroleum consumption (transportation sector) 1995–2035, 4, 5(F)
  - petroleum production/consumption (transportation sector) 1973–2035, 4, 4(F)
- TRIP effect, 52, 120, 120(F), 123, 140, 141
- TRIP steels. *See* transformation-induced plasticity (TRIP) steels
- true stress-strain curves
  - AUST SS, 154(F)
  - MS steels, 129–130, 130(F)
  - TRIP steels, 121, 122(T)
- TTT diagram. *See* time-temperature-transformation (TTT) diagram
- TWC. *See* tailor welded coils (TWC)
- twin boundaries, 56, 56(F), 118
- twin boundary hardening, 56, 56(F)
- twinning
  - crystal twins, 56
  - fundamentals, 52–53, 52(F)
  - hexagonal crystals, 136
  - mechanical twins, 56
  - twin boundary hardening, 56
  - twins, formation of, 52–53
  - TWIP grades, 48
- twinning-induced plasticity (TWIP) grades
  - applications, 48
  - dislocation glide, 48
  - ductility, 48
  - manganese, 48
  - mechanical properties, 48
  - strain-hardening rates, 48
- twinning-induced plasticity (TWIP) steels
  - alloying elements, 135, 137
  - applications, 149
  - attributes, 148–149
  - carbon content, 135, 139, 140–141
  - compositions, 137, 137(T)



- crashworthiness, 80
  - deformation mechanisms, 140–142(F), 143(F)
    - alloying content, 142
    - dislocation glide, 142
    - dislocation pileup at twin boundary, 143(F)
    - mechanical twins, 141–142, 142(F)
    - SFE, 140
    - SFE and deformation mechanism, relationship between, 141(F)
    - strain-hardening mechanism, 142
    - twins act as obstacles to dislocation glide, 141(F)
    - TWIP effect, 140
    - work-hardening rate, 142
  - energy-absorption capabilities, 89, 90(F)
  - engineering stress-strain curve, 72, 73(F)
  - Fe-22Mn-0.52C, fatigue performance of, 77
  - ferrite, 137
  - formability, 18, 148, 148(F)
  - hardening, 148, 148(F)
  - manganese content, 135
  - mechanical properties, 142–148(F,T)
    - engineering stress-strain curve (Fe-22Mn-0.6C), 144(F)
    - manganese content, 145(T)
    - mechanical properties, 144(T)
    - room-temperature dynamic strain aging, 146–147
    - strain-hardening exponent, 142
    - stress-strain curves, 143–146(F), 147–148, 147(F)
    - tensile strength, 142
    - tensile strength-elongation space, 143, 143(F)
    - true stress-strain curve (Fe-22Mn-0.6C), 144(F)
  - Microstructure Evolution in TWIP Steel, 210–211(F)
  - overview, 17–18, 48, 135
  - processing of, 139–140(F,T)
  - SFE, 135, 137
  - stacking faults, 136
  - strain-hardening, 135, 140, 141(F), 142
  - tensile strength, 18
  - tensile strength-total elongation space, 143, 143(F)
  - thermodynamics of, 138–139(F)
    - metastable (nonequilibrium) Fe-Mn phase diagram, 138–139, 138(F)
    - microstructure, 138–139
    - stable room temperature austenite, 139
  - total elongation, 143, 143(F)
  - twins, 135–136, 136(F)
    - TWIP effect, 137
    - Vickers microhardness tests, 139–140
    - welding, 197
    - work-hardening, 80, 206, 210
  - twinning-induced plasticity (TWIP) steels, types
    - TWIP Fe-18Mn-0.6, 139
    - TWIP Fe-18Mn-0.6C, 146
    - TWIP Fe-18Mn-0.6C-1.5Al, 147–148, 147(F)
    - TWIP Fe-20Mn-1.2C, 142(F)
    - TWIP Fe-22Mn-0.6C, 143, 144, 144(F), 146
    - TWIP Fe-24Mn, 137, 137(T), 138(F), 139, 139(F), 140(F,T), 145–146, 146(F), 147(F)
    - TWIP Fe-29Mn, 139
    - TWIP Fe-30Mn, 137, 137(T), 138(F), 139, 145, 145(F), 146(F)
    - TWIP Fe-31Mn, 139
  - twins, 135–136(F)
    - annealing twins, 56, 135, 207
    - atomic planes, 136
    - deformation by twinning, 136(F)
    - mechanical twins, 135
    - in microstructures, 136
    - slip, 136
    - twinning, 136
  - TWIP effect, 52, 137, 140–141
  - TWIP grades. *See* twinning-induced plasticity (TWIP) grades
  - TWIP steels. *See* twinning-induced plasticity (TWIP) steels
- ## U
- U-channel draw test, 182, 182(F)
  - U-channel forming
    - angular change, 182–183, 183(F)
    - curl, 182–183, 183(F)
    - springback, 180–181(F), 183
    - springback U-channel draw test, 182(F)
  - ULSAB. *See* Ultra-Light Steel Auto Body (ULSAB)
  - ULSAB-AVC. *See* Ultra-Light Steel Auto Body—Advanced Vehicle Concepts (ULSAB-AVC)
  - ULSAC. *See* Ultra-Light Steel Auto Closures (ULSAC)
  - ULSAS. *See* Ultra-Light Steel Auto Suspension (ULSAS)
  - ultimate tensile strength (UTS)
    - AHSS, 59–60
    - defined, 72
    - DP steels, 95, 97, 196
    - MS grades, 48
    - ULSAB, defined by, 42

ultrafine grain (UFG) material, 97(F), 211(T), 212

ultrafine-grained alloy, 64

Ultra-Light Steel Auto Body (ULSAB), 10–11, 20, 200, 226(F)

Ultra-Light Steel Auto Body—Advanced Vehicle Concepts (ULSAB-AVC), 11, 59, 200, 203, 204(F)

Ultra-Light Steel Auto Closures (ULSAC), 10–11, 200

Ultra-Light Steel Auto Suspension (ULSAS), 200

uniaxial tensile test, 81

uniaxial tensile testing, 81, 177–178

uniaxial tensile tests

- AUST SS, 154(F)
- DP steels, 154(F)

United States Automotive Materials Partnership (USAMP), 203, 204, 205, 273

United States Council for Automotive Research (USCAR), 203–204, 239

United States Council for Automotive Research/U.S. Automotive Materials Partnership (USCAR/USAMP), 203–205, 273

upper yield strength (UYS), 92(F)

urban pollution, 2

U.S. Department of Energy (DOE), 204, 252–253, 273

USAMP. *See* United States Automotive Materials Partnership (USAMP)

USA-TEAM partnership, 204

USCAR. *See* United States Council for Automotive Research (USCAR)

USCAR/USAMP. *See* United States Council for Automotive Research/U.S. Automotive Materials Partnership (USCAR/USAMP)

US-DRIVE, 204

## V

vanadium

- alloy steels, 44
- CP grades, 47
- CP steels, 107, 108
- HSLA, 45
- MS grades, 48
- MS steels, 128
- TRIP steels, 115

vanadium carbide, 191

variable binder force (VBF), 234

vehicle weight

- distribution of, 9
- Henry Ford's observations, 7, 8(F)
- reducing, strategies for, 9

reduction and fuel economy, relationship between, 9

reduction of, 8–9, 8(F)

Vickers microhardness tests, 139–140

## W

welding, 194–197(F)

- AHSS temperature sensitivity, 196
- arc welding, 195, 196, 221
- AUST SS, 197
- automotive industry, 195
- basic welding positions, 221(F)
- categories, 194–195
- description of, 194
- flame straightening, 221
- fusion welding, 195
- GMAW, 219–220(F), 221(F)
- laser welding, 195, 197
- liquid zinc embrittlement, 197
- mechanical properties, effect on, 196–197
- resistance spot welding, 195–196(F), 197, 221, 222(F)
- sensitization in heat-affected zone, 197
- solid-state welding, 195
- stainless steels, 197
- tempering, 196
- thermal cycling, 196
- UTS (DP 600), 196

welding guidelines, 217–221(F), 222(F)

- arc welding, 221
- ASP study (auto body structural components), 217–218
- ASP study (GMAW chassis structures), 219–220(F), 221(F)
- ASP study (resistance welding performance), 218–219(F)
- basic welding positions, 221(F)
- chassis structures of all grades, 220, 220(F)
- flame straightening, 221
- fusion welding processes, 217
- joining, 220–221
- overview, 217
- resistance spot welding, 221, 222(F)
- spot weld, 218, 218(F)

work-hardening

- AHSS, 80, 178
- bake hardening, comparison, 92, 93(F)
- definition of, 26
- DP steels, 73, 95, 105, 183
- examples, 54
- Fe-30Mn, 206
- novel processing methods, 268
- stress-strain curves, 178

- third generation AHSS, 265
- TRIP steels, 67, 119, 121–122, 206
- TWIP steels, 80, 142, 206, 210
- uniaxial tension, 81
- World Steel Association, 200, 249–250, 258, 258(T)
- WorldAutoSteel (WAS), 199, 200, 215, 216, 259, 260
- wrinkles, 228, 229–230, 236, 241
- wrought steels, 24, 24(F)

## Y

- yield strength (YS)
  - AHSS, 59–60
  - AUST SS, 153
  - bake hardening process, 92(F), 93(F)
  - defined, 72
  - HSLA, 45

- importance of, 38
- martensite, 132
- MS steels, 130
- springback, 181–182, 182(F)
- steel, 39, 39(T)
- toughness, 89–90, 90(F)
- ULSAB, defined by, 42
- work hardening, 92–93, 93(F)
- yield stress
  - AHSS, 76
  - AUST SS, 151–152
  - conventional steels, 74(F)
  - DP steels, 77, 78(F)
  - hot forming process, 192
  - HSLA, 77, 78(F)
  - plastic zone, 89
  - tempered martensite, 34, 35(F), 132, 132(F)
  - toughness, 89
  - TRIP steels, 77, 78(F), 144(T)