MECH 401
Mechanical Design Applications

Fundamentals Section – Master Notes

Spring 2004
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Rice University

Course Information

- Meeting time
  - T-Th 8:00 – 9:15
  - DH 1042
- Prerequisites
  - MECH 311 or CIVI 300
- Texts
  - Mechanical Engineering Design
  - by Shigley, Mischke, and Budynas
- Goals
  - Provide design skills to support MECH 407/408 projects
  - Understand the application of engineering analysis to common machine elements
  - Enhance your ability to solve practical design problems using free body diagrams, Mohr's circle, beam analysis, etc.

- M. K. O'Malley, PhD
  - MEB 216
  - Phone: 3545
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  - Office hours:
    - Monday 11:00 AM – 12:00 PM
  - Fundamentals
- D. M. McStravick, PhD, P.E.
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  - Office hours:
    - TBA
  - Applications

Syllabus

- General policies
- (20%) Homework
  - Late homework is not accepted
  - Neatness counts!
- (10%) In-class mini-tests (6 total)
- (20%) Project

Overview and introduction of design of machine elements

- Two primary phases of design
  1. Inventive phase – creative aspect
  2. Engineering phase – understanding of physical reality aspect
  - (1) makes a design unique or clever (MECH 407/408)
  - (2) makes a design work
- This course will focus on 2nd aspect, making our designs work

"Understanding of physical reality"

- Theoretical results
- Empirical results

- Theory helps us understand physical phenomena so that we can address design at a fundamental level
- Theory often falls short, however, in describing complex phenomena, so we must use empirical results

Systems of Units

- Appendix lists units (English, SI), conversion factors, and abbreviations
- Unit
  - A specified amount of a physical quantity by which through comparison another quantity of the same kind is measured
  - Examples?
    - Length, time, temperature
- 2 basic systems of units
  - U.S. customary foot-pound-second system (fps)
  - International System of Units (SI)

Primary dimensions

- Sufficient to conceive of and measure other dimensions
- Examples?

Secondary dimensions

- Measured in terms of primary dimensions
- Examples?

U.S. customary

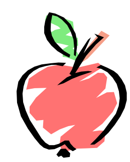
- Foot-pound-second (fps)
- Inch-pound-second (ips)

- FPS:
  - Force – pound-force
  - 1000 lbf = 1 kilopound = 1 kip
  - Derived unit of mass is lbf-s^2/ft (slug)

SI (mLt)

- Mass, length, and time
- m – kg
- L – m
- t – s
- F is secondary (Newtons)
- 1 N ~ 1 apple

- F = ma
- 1 N = 1 kg·m/s^2



Methodology

- Solving machine component problems
  - Step 1
    - Define/understand
  - Step 2
    - Define/synthesize the structure
    - ID interactions
    - Draw diagrams
  - Step 3
    - Analyze/solve using:
      - Appropriate assumptions
      - Physical laws
      - Relationships
      - Rules
  - Step 4
    - Check – is the answer reasonable?

Homework format

- Start each problem on a new page
- One side of sheet only
- Use straight-edge, work neatly

- Known:
  - Problem statement
  - Schematic
  - Given data
  - Material properties
- Find:
  - Concisely state what is to be determined
- Solution:
  - Assumptions
  - Design decisions
  - Equations (make number substitutions last)
  - Comments (when appropriate)

Introduction to reliability engineering

- We cannot assume that all the quantities that we utilize in failure analysis are deterministic quantities
  - "We know their values absolutely!"
- In many cases, especially in manufacturing, this is NOT the case
  - A part dimension that is supposed to be 1" in diameter might vary between 0.95 and 1.05 inches due to variation in machining process (tool wear)
- Statistics and random variable methods enable designers to deal with variable quantities
  - Reliability Engineering

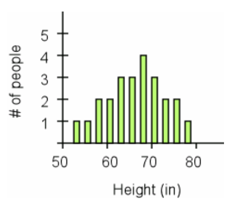
Definitions

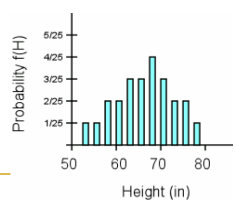
- Random (stochastic) variable
  - A real-valued set of numbers that result from a random process or are descriptive of a random relationship
- For example, if I were to construct a list of everybody's height in this class…
  - Then height, H, would be considered a random variable

Sample #	H (height in inches)
1	
2	
3	
4	

Height example

- Let's say there are 25 people in this class.
- Construct a histogram to represent the data
- If we divide the (# of people) axis by the total number of people sampled, then we have
  - Probability density function (pdf)
  - PDF gives the probability that a random variable will have a certain value
  - Same shape as the histogram





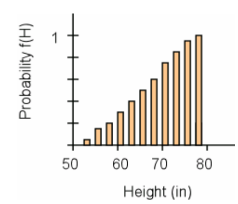
Height example

- If we integrate this "function", we get the cumulative distribution function (cdf)
  - Gives the probability (likelihood) that a random variable will be less than or equal to a given value
  - For a random variable *x*,

$$\lim_{x\to\infty} F(x) = 1$$

  - For a discrete random variable,

$$F(x_i) = \sum_{x_j \le x_i} f(x_j)$$



Characterizing random variables

- A random variable is not a scalar, but rather a vector
- In this deterministic case, we can say
  - x = 63.5 inches
- This is a scalar, since it has only a single value
- In the stochastic case, we know that the variable x can take on many values
  - x = 63.5, 68.7, 62.1, etc
- We define the discrete random variable **x** to be a vector of the samples x_1, x_2, … , x_n
  - We refer to **x** as the variate

$$\mathbf{x} = \begin{bmatrix} x_1 \\ \cdot \\ \cdot \\ \cdot \\ x_n \end{bmatrix}$$

  - Note, in this sense, a vector can be considered a collection of numbers, not a quantity with direction and magnitude
  - It is helpful to have some scalar quantities that characterize the random variable vector
    - Direction and magnitude won't do the trick!

Scalar quantities to characterize **x**

- Mean

$$\hat{\mu} \equiv \frac{x_1 + x_2 + \ldots + x_n}{N} = \frac{1}{N}\sum_{i=1}^{N} x_i$$

  - A measure of the central value of a distribution
- Standard deviation

$$\hat{\sigma} \equiv \left[\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \hat{\mu})^2\right]^{1/2}$$

  - A measure of the dispersion or distribution of data
  - Note – this is most useful as a comparative measure
    - By itself, it's not particularly useful!
  - Some people use 1/N instead of 1/(N-1), but 1/(N-1) typically gives better results for small N
- The notation for mean and standard deviation of a variate are as follows:

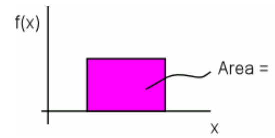
$$\mathbf{x} = (\hat{\mu}, \hat{\sigma})$$

Reliability Engineering, Cont.

- Terminology
  - Population
    - The total set of elements in which we are interested
  - Sample
    - A randomly selected subset of the total population on which measurements are taken
- Describing the shape of a distribution
  - Uniform
  - Normal } We'll look at these
  - Log Normal
  - Weibull

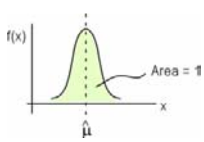
Uniform distribution

- Simplest
- All elements have the same value
- Area equal to 1 implies that all samples in the given range of x have the same value of f(x), where f(x) describes the distribution

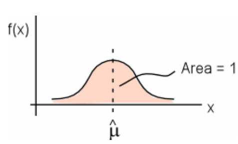


Normal distribution

- Also called Gaussian distribution
- $$f(x) = \frac{1}{\hat{\sigma}\sqrt{2\pi}} e^{\left[-\frac{1}{2}\left(\frac{x-\hat{\mu}}{\hat{\sigma}}\right)^2\right]}$$



Small standard deviation ($\hat{\sigma}$)



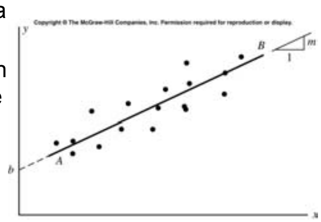
Large standard deviation ($\hat{\sigma}$)

Notation

- Normal distribution with mean and standard deviation: $$\mathbf{x} = \mathbf{N}(\hat{\mu}, \hat{\sigma})$$
- This IS a complete characterization
- CDF of Normal (Gaussian) Distribution cannot be found in closed form
- Generalized description of normal CDF:
  - $\mathbf{Z} = \frac{\mathbf{x} - \hat{\mu}}{\hat{\sigma}}$ Note: $F(x) = \int_{-\infty}^{x} f(u)du$

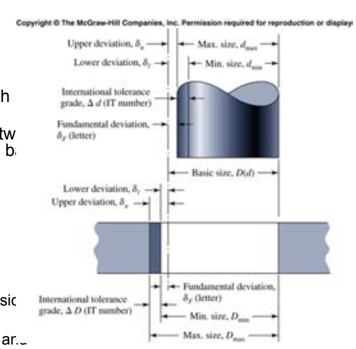
Linear Regression

- Obtaining a best-fit to a set of data points
- Linear regression when best fit is a straight line
- Correlation coefficient tells you how good the fit is



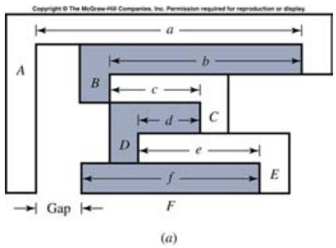
Limits and fits

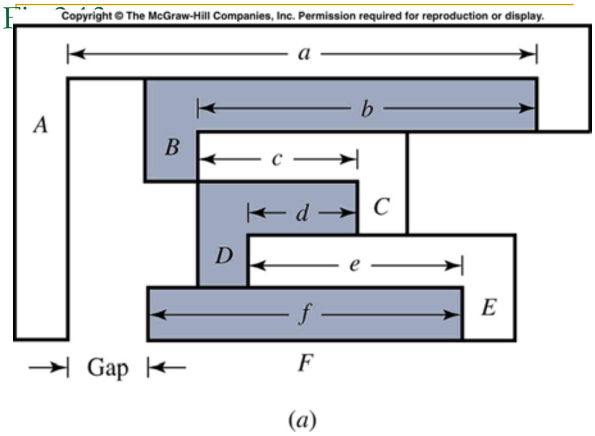
- Capital letters – hole
- Lowercase letters – shaft
- Basic size – same for both members of the fit
- Deviation – difference betw a size and corresponding b size
- Upper deviation
  - Max-size
- Lower deviation
  - Min-size
- Fundamental deviation
  - Either upper or lower, whichever is closer to basic
- Tolerance
  - Difference between max ar... min deviations



Dimensions and tolerances

- Nominal size
- Basic size
- Limits
- Tolerance
- Clearance
- Interference
- Allowance





Materials and Processes

- Must always make “things” out of materials
- Must be able to manufacture this “thing”
- Topics first introduced in Materials Science course (MSCI 301)
- How do we determine the properties of a material?
  - Tables
- How were these values determined?
  - Generally via destructive testing

Material properties

- Listed in tables
- Statistical variation
- Values listed are minimums
- Best data from testing of prototypes under intended loading conditions

Material parameters

- Parameters of interest in material selection for design?
  - Strength
  - Stiffness
  - Weight
  - Toughness
  - Conductivity
  - Thermal
  - Corrosion resistance

(Strength, Stiffness, Weight: PRIMARY CONCERNS)

Primary parameters of interest in material selection

- Strength
  - Amount of load (or weight, or force) a part can take before breaking or bending
- Stiffness
  - Amount of deflection or deformation for a given load
- Weight

- All of these depend on geometry
  - **EXTENSIVE** values
- We would like to derive results that are independent of size (geometry)
  - **INTENSIVE** values

Extensive vs. Intensive values

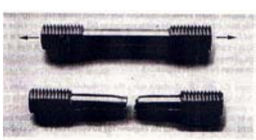
- Extensive
  - Weight (kg)
  - Strength (N)
  - Stiffness (N/m)
- Intensive
  - Density (kg/m^3)
  - Yield strength or Ultimate Strength (N/m^2)
  - Modulus of Elasticity (N/m^2)

How do we determine these values?

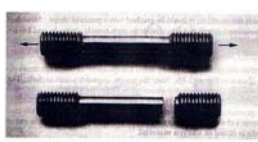
- Types of quasistatic material testing
  - Tension
  - Compression
  - Bending
  - Torsion

Tensile tests specimens

What is the difference between these specimens?



Mild ductile steel tensile test specimen



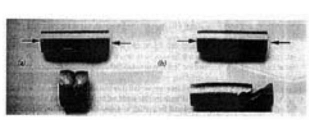
Brittle cast iron tensile test specimen

Tensile testing

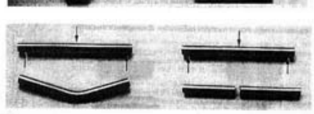
- Best for general case
- Why?
  - Uniform loading and uniform cross-section generate uniform stress
  - Compression poses stability problems (buckling)
  - Torsion and bending impose non-uniform stress

Other test specimens – Ductile and Brittle

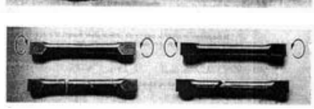
Compression



Bending

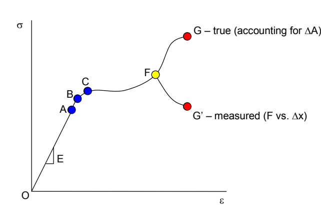


Torsion



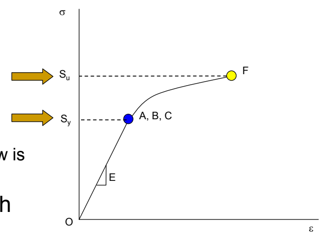
Stress-Strain (σ-ε) Curves

- Point A – Proportional limit
- Point B – Elastic limit
- Point C – Yield point
  - Usually defined by permanent set of $\varepsilon = 0.002$ (0.2% offset)
- For purposes of design, we often assume A~B~C, and call this the yield point
- Slope of O-A = E
  - Young's Modulus
  - Modulus of elasticity
  - Like stiffness
- Point F – Onset of failure
- Point G, G' - Fracture



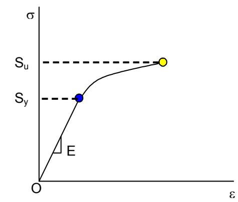
Important design considerations

- S_y = Yield strength
  - It is the stress level…
    - That will result in permanent set
    - At which material undergoes marked decrease in stiffness
    - At which Hooke's Law is no longer valid
- S_u = Ultimate strength
  - Stress level that will result in fracture

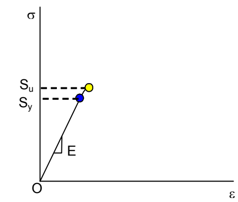


Ductile vs. Brittle Material Behavior

- Ductile material
  - Sustains significant plastic deformation prior to fracture



- Brittle material
  - No significant plastic deformation before fracture



Ductile vs. Brittle Material Behavior

- The only true means of determining if a material is ductile or brittle is by testing it (tensile test)
- Note: The same alloy can be either ductile or brittle, depending upon temperature and/or how it was formed
- Some general indications of brittle behavior
  - Glass, ceramic, and wood
  - Cast ferrous alloys
  - Materials in extreme cold temperatures
  - Also, if you can't find S_y in a handbook (only S_u given)

Fatigue testing – measuring endurance

- Most machines are loaded cyclically
  - Any piece of rotating machinery
- Strength decreases over time
  - "Fatigue strength" depends on number of cycles and the material

- How to test?
  - Use a rotating beam
  - More often vary axial loading over time

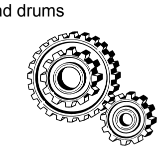
Common metals in machine design

- Magnesium
  - Specific stiffness ~ 25 MPa/(kg/m^3)
  - Extremely light (~1/5 steel)
  - Extremely flammable

- Aluminum (very common)
  - Specific stiffness ~ 26
  - Stiffness-to-weight and strength-to-weight comparable to steel
  - 1/3 stiffness of steel
  - 1/3 density of steel

More metals…

- Gray cast iron
  - Specific stiffness ~ 15
  - Decent strength
  - Used where casting makes sense and weight doesn't matter
    - Gears, engine blocks, brake disks and drums
- Brass, bronze
  - Generally soft
  - Good for bearings (bronze)

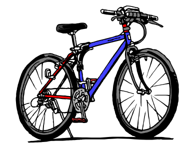


More metals…

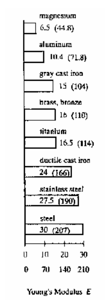
- Titanium
  - Specific stiffness ~ 26
  - Excellent strength-to-weight
  - Non-magnetic
  - Non-corrosive (implants)
  - Can be cast
  - Expensive
- Ductile cast iron
  - Stronger than gray cast iron
  - Heavy-duty gears, automobile door hinges

More metals…

- Stainless steel
  - Non-magnetic
  - Much less corrosive than steel
  - Difficult to machine
- Steel
  - Specific stiffness ~ 27
  - Excellent fatigue properties
  - Good stiffness-to-weight
  - Better alloys have excellent strength-to-weight
    - Chromoly bicycle frames



Comparison of Young's Modulus for various metals



Question…

- Does all steel have the same strength?
- Does all steel have the same stiffness?

- Strength (S_y, S_u) depends on alloy and state
- Stiffness (E) depends only on metal type
  - i.e., E is a property of the metal and does not change with alloy or state

So what affects the strength of a metal?

- Two primary forms –
  - Alloying
  - Crystal state

- Metal alloys
  - Adding certain elements in trace amounts to a metal can significantly change its strength
  - Since the alloying elements are present in trace amounts, they don't significantly alter modulus (stiffness) or density

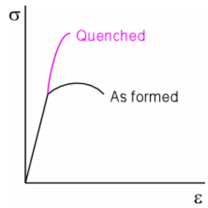
Alloying

- Steel – Primary alloying elements:
  - Manganese
  - Nickel
  - Chromium
  - Molybdenum
  - Vanadium

- The alloy is identified by AISI/SAE or ASTM numbering system
  - AISI – American Iron and Steel Institute
  - SAE – Society of Automotive Engineering
  - ASTM – American Society for Testing and Materials

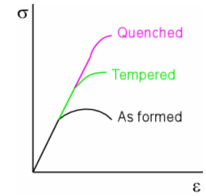
Altering crystal state

- Crystal state of steel can be altered by heat treatment or cold working
- Quenching
  - Heat to very high (~1400ºF) temp and cool rather suddenly by immersion in water
  - Creates crystal structure called martensite which is extremely strong but brittle



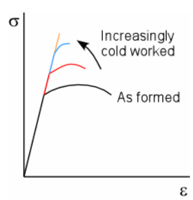
More methods…

- Tempering
  - Reheat to moderate temperature and cool slowly
  - Adds ductility at the expense of decreased strength
- Annealing
  - Resets the alloy to original low strength, ductile state
  - Reheat alloy above critical temperature and allow to cool slowly



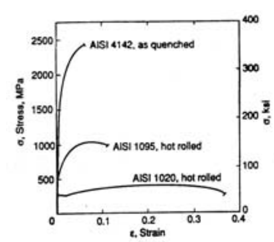
More methods…

- Normalizing
  - Between tempering and annealing
- Cold working
  - Another means of increasing strength at the expense of ductility
- Hot working
  - Reheating as the metal is deformed to maintain ductility



Question

- If you're going to have a piece of metal machined, would you rather use a cold worked or hot worked metal?



Steel numbering systems

- Used to define alloying elements and carbon content
- 1st two digits
  - Indicate principal alloying elements
- Last 2 digits
  - Indicate amount of carbon present
  - In 100ths of a percent

Steel number systems

- Plain carbon steel
  - 1st digit – 1
  - 2nd digit – 0
  - No alloys other than carbon are present
  - AISI 1005-1030: Low-carbon steels
  - AISI 1035-1055: Medium-carbon steels
  - AISI 1060-1085: High-carbon steels
  - AISI 11xx series adds sulphur
    - Improves machinability
    - Called free-machining steels
    - Not considered alloys –
      - Sulphur does not improve mechanical properties
      - Makes it brittle

Steel number systems

- Alloy steels
  - Have various elements added in small quantities
  - Improve material's
    - Strength
    - Hardenability
    - Temperature resistance
    - Corrosion resistance
    - Other…
  - Nickel –
    - Improve strength without loss of ductility
    - Enhances case hardenability
  - Molybdenum
    - In combination with nickel and/or chromium
    - Adds hardness
    - Reduces brittleness
    - Increases toughness
  - Other alloys used to achieve specific properties

Steel numbering systems

- Tool steels
  - Medium- to high- carbon alloy steels
  - Especially formulated to give:
    - Very high hardness
    - Wear resistance
    - Sufficient toughness to resist shock loads experienced in machining
- Stainless steels
  - Alloy steels with at least 10% chromium
  - Improved corrosion resistance over plain or alloy steels

Steel numbering systems

- Martensitic stainless steels
  - 11.5 to 15% Cr and 0.15 to 1.2% C
  - Magnetic
  - Can be hardened by heat treatment
  - Cutlery
- Ferritic stainless steel
  - Over 16% Cr and low C content
  - Magnetic
  - Soft
  - Ductile
  - Not heat treatable
  - Cookware
- Both martensitic and ferritic called 400 series

Steel numbering systems

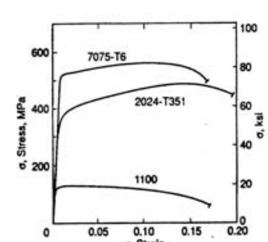
- Austenitic stainless steel
  - 17 to 25% Cr and 10 to 20% nickel
  - Better corrosion resistance (due to Ni)
  - Nonmagnetic
  - Excellent ductility and toughness
  - Cannot be hardened except by cold working
  - 300 series
- 300 series very weldable
- 400 series less so

Aluminum alloys

- Principal alloying elements
  - Copper
  - Manganese
  - Silicon
  - Zinc
- Alloys are designated by the Aluminum Association numbering system

Aluminum alloys, cont.

- Aluminum alloys are also heat-treatable, as designated by the –T classification in the AA numbering system



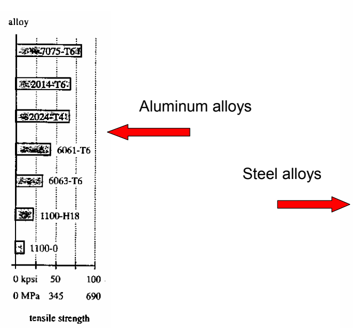
Aluminum alloys

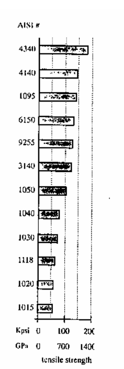
- Wrought-aluminum alloys
  - Available in wide variety of stock shapes
    - I-beams, angles, channels, bars, etc
  - 1st digit indicates principal alloying element
  - Hardness indicated by a suffix containing a letter and up to 3 numbers
  - Most commonly available and used in machine design applications:
    - 2000 series
    - 6000 series

Aluminum alloys

- 2024
  - Oldest alloy
  - Among the most machinable
  - One of the strongest Al alloys
  - High fatigue strength
  - Poor weldability and formability
- 6061
  - Widely used in structural applications
  - Excellent weldabilty
  - Lower fatigue strength than 2024
  - Easily machined and popular for extrusion
- 7000 series
  - Aircraft aluminum
  - Strongest alloys

Tensile strengths of metals





Look-up tables for Material properties (in the appendix)

1 AISI NO	2 TREATMENT	3 TEMPERATURE, C (F)	4 TENSILE STRENGTH, MPa (kpsi)	5 YIELD STRENGTH MPa (kpsi)
1030	Q&T*	205 (400)	848 (123)	648 (94)
	Q&T*	315 (600)	800 (116)	621 (90)
	Q&T*	425 (800)	731 (106)	579 (84)
	Q&T*	540 (1000)	669 (97)	517 (75)
	Q&T*	650 (1200)	586 (85)	441 (64)
	Normalized	925 (1700)	521 (75)	345 (50)
	Annealed	870 (1600)	430 (62)	317 (46)
1040	Q&T	205 (400)	779 (113)	593 (86)
	Q&T	425 (800)	758 (110)	552 (80)
	Q&T	650 (1200)	634 (92)	434 (63)
	Normalized	900 (1650)	590 (86)	374 (54)
	Annealed	790 (1450)	519 (75)	353 (51)
1050	Q&T*	205 (400)	1120 (163)	807 (117)
	Q&T*	425 (800)	1090 (158)	793 (115)
	Q&T*	650 (1200)	717 (104)	538 (78)
	Normalized	900 (1650)	748 (108)	427 (62)
	Annealed	790 (1450)	636 (92)	365 (53)
1060	Q&T	425 (800)	1080 (156)	765 (111)
	Q&T	540 (1000)	965 (140)	669 (97)
	Q&T	650 (1200)	800 (116)	524 (76)
	Normalized	900 (1650)	776 (112)	421 (61)
	Annealed	790 (1450)	626 (91)	372 (54)
1095	Q&T	315 (600)	1260 (183)	813 (118)
	Q&T	425 (800)	1210 (176)	772 (112)
	Q&T	540 (1000)	1090 (158)	676 (98)
	Q&T	650 (1200)	896 (130)	552 (80)
	Normalized	900 (1650)	1010 (147)	500 (72)
	Annealed	790 (1450)	658 (95)	380 (55)
1141	Q&T	315 (600)	1460 (212)	1280 (186)
	Q&T	540 (1000)	896 (130)	765 (111)
4130	Q&T*	205 (400)	1630 (236)	1460 (212)
	Q&T*	315 (600)	1500 (217)	1380 (200)
	Q&T*	425 (800)	1280 (186)	1190 (173)
	Q&T*	540 (1000)	1030 (150)	910 (132)
	Q&T*	650 (1200)	814 (118)	703 (102)
	Normalized	870 (1600)	670 (97)	436 (63)
	Annealed	865 (1585)	560 (81)	361 (52)
4140	Q&T	205 (400)	1770 (257)	1640 (238)
	Q&T	315 (600)	1550 (225)	1430 (208)