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Preface

Mold design has been more of a technical trade than an engineering process. Traditionally, practitioners have shared standard practices and learned tricks of the trade to develop sophisticated molds that often exceed customer expectations.

However, the lack of fundamental engineering analysis during mold design frequently results in molds that may fail and require extensive rework, produce moldings of inferior quality, or are less cost effective than may have been possible. Indeed, it has been estimated that on average 49 out of 50 molds require some modifications during the mold start-up process. Many times, mold designers and end-users may not know how much money was "left on the table".

The word "engineering" in the title of this book implies a methodical and analytical approach to mold design. The engineer who understands the causality between design decisions and mold performance has the ability to make better and more informed decisions on an application by application basis. Such decision making competence is a competitive enabler by supporting the development of custom mold designs that outperform molds developed according to standard practices. The proficient engineer also avoids the cost and time needed to delegate decision to other parties, who are not necessarily more competent.

The book has been written as a teaching text, but is geared towards professionals working in a tightly integrated supply chain including product designers, mold designers, and injection molders. Compared to most handbooks, this textbook provides worked examples with rigorous analysis and detailed discussion of vital mold engineering concepts. It should be understood that this textbook purposefully investigates the prevalent and fundamental aspects of injection mold engineering.

I hope that *Injection Mold Design Engineering* is accessible and useful to all who read it. I welcome your feedback and partnership for future improvements.

Best wishes,

David Kazmer, P. E., Ph. D.

Lowell, Massachusetts
June 1, 2007

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Nomenclature

Mold engineering requires analysis, and so an extensive nomenclature has been developed. L, W, and H refer to the length, width, and height dimensions as shown in Figure 1.

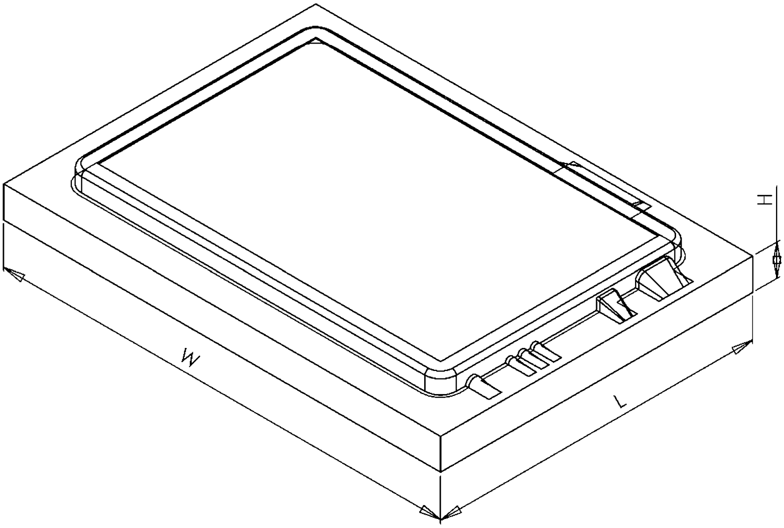

Figure 1: Length, width, and height nomenclature

Variable names have been selected and consistently used as expected (e.g., T for temperature, C for cost, P for pressure, etc.). R refers to rate-related constants (with time dependence) and κ refers to monetary constants (with cost dependence). To provide clarity, subscripts are unabbreviated throughout most of the book. The nomenclature for many of the variables and their units are as follows.

Table 1: Nomenclature

Variable	Meaning
α	Thermal diffusivity [m^2/s]
β	Compressibility [1/MPa]
δ	Deflection [m]
δ_{bending}	Deflection due to bending [m]
$\delta_{\text{compression}}$	Deflection due to compression [m]
δ_{total}	Deflection due to bending and compression [m]
ε	Strain [m/m]

Variable	Meaning
$\varepsilon_{plastic}$	Plastic's strain to failure [%]
$\dot{\gamma}$	Shear rate [1/s]
$\dot{\gamma}_{max}$	Maximum allowable shear rate for a plastic melt being molded [1/s]
η	Viscosity [Pa s]
κ	Thermal conductivity [W/m°C]
κ_{insert}	Cost per unit volume of core and cavity insert materials [$/m^3]
κ_{mold}	Cost of mold metal per kilogram [$/kg]
$\kappa_{plastic}$	Cost of plastic per kilogram [$/kg]
λ	Tolerance limit [m]
μ	Apparent viscosity for Newtonian model [Pa]
μ_{static}	Coefficient of static friction [–]
ρ	Density [kg/m^3]
ρ_{insert}	Density of core and cavity insert materials [kg/m^3]
$\rho_{plastic}$	Density of plastic [kg/m^3]
ϕ	Draft angle [°]
θ	Draft angle [°]
$\sigma_{buckling}$	Stress level at which column buckles [MPa]
σ_{cyclic}	Imposed cyclic stress [MPa]
$\sigma_{endurance}$	Maximum allowable stress given cyclic loading [MPa]
σ_{hoop}	Hoop stress [MPa]
σ_{limit}	Maximum allowable stress given cyclic loading or yielding [MPa]
σ_{yield}	Maximum allowable stress given yield failure [MPa]
τ	Shear stress [Pa]
ν	Specific volume [–]
$\Omega_{ejectors}$	Total perimeter of all ejectors [m]
$A_{cavity\_Projected}$	Projected area of the mold cavity [m^2]
$A_{compression}$	Area exposed to compressive stress [m^2]
A_{eff}	Effective area under stress [m^2]
$A_{ejectors}$	Total area of all ejectors [m^2]
A_{part}	Total surface area of the molded part
A_{shear}	Area exposed to shear stress [m^2]
C	Tolerance coefficient for a standard fit [m$^{2/3}$]
$C_{auxiliaries}$	Total cost of all auxiliaries [$]

Variable	Meaning
C_{inserts}	Total cost of all cavities [$]
$C_{\text{insert\_finishing}}$	Cost of finishing one set of core and cavity inserts [$]
$C_{\text{insert\_machining}}$	Cost of machining one set of core and cavity inserts [$]
$C_{\text{insert\_materials}}$	Cost of materials for one set of core and cavity inserts [$]
C_{mold}	Total cost of purchasing mold [$]
$C_{\text{mold/part}}$	Cost of purchasing mold amortized across total production quantity [$]
$C_{\text{mold\_base}}$	Total cost of mold base and modifications [$]
$C_{\text{mold\_customization}}$	Total cost of all customizations of mold base [$]
$C_{\text{mold\_steel}}$	Initial purchase cost of mold base or steel [$]
C_{part}	Total cost per molded part [$]
$C_{\text{plastic/part}}$	Cost of material used in molding one part [$]
$C_{\text{process/part}}$	Cost of machinery and labor used to mold one part [$]
CP_{plastic}	Plastic's specific heat [J/kg °C]
CTE	Coefficient of thermal expansion [1/°C]
$CVTE$	Coefficient of volumetric thermal expansion [1/°C]
D	Diameter [m]
$D_{\text{hydraulic}}$	Hydraulic diameter of runner segment [m]
D_{pin}	Diameter of ejector pin [m]
E	Elastic modulus [GPa]
f	Factory of safety [–]
$f_{\text{cavity\_complexity}}$	Factor related to the complexity of the cavity
$f_{\text{cavity\_discount}}$	Discount factor related to production of multiple sets of core and cavity inserts
$f_{\text{cycle\_efficiency}}$	Factor associated with the efficiency of operating the molding machine
$f_{\text{efficiency}}$	Factor related to the overall efficiency of all machining operations
$f_{\text{feed\_waste}}$	Factor associated with material wasted in molding the feed system
$f^{i}_{\text{cavity\_customizing}}$	Factor associated with customization of one set of core and cavity inserts
$f^{i}_{\text{finishing}}$	Percentage of the molded part's surface area to be finished in the manner i
$f^{i}_{\text{mold\_customizing}}$	Factor associated with customizing mold base
f_{machine}	Factor associated with cost of operating different molding machines and auxiliaries
$f_{\text{machining}}$	Factor related to the average material removal rate of all machining processes relative to standard milling
$f_{\text{maintenance}}$	Mold lifetime maintenance factor
f_{wear}	Factor associated with maintenance due to mold wear

Variable	Meaning
f_{yield}	Fraction of molded parts that are good
F	Force [N]
F_{buckling}	Critical load at which column buckles [N]
F_{clamp}	Mold force tonnage [metric tons, t]
F_{eject}	Ejection force [N]
$F_{\text{insertion}}$	Insertion force for interference fit [N]
F_{tensile}	Maximum tensile force for a socket head cap screw [N]
h	Nominal cavity wall thickness [m]
h_{∞}	Heat transfer coefficient [W/°C]
H_{cavity}	Height of cavity inserts [m]
H_{core}	Height of core inserts [m]
H_{inserts}	Combined height of core and cavity inserts [m]
H_{Line}	Distance from cavity surface to the center of cooling line [m]
H_{mold}	Total stack height of mold [m]
H_{part}	Maximum height of molded part [m]
I	Moment of inertia [m^4]
K	Stress concentration factor [–]
k, n	Reference viscosity and power law index per the power law model [Pa^n, –]
k_{plastic}	Plastic's thermal conductivity [W/m °C]
L_{inserts}	Length of core and cavity inserts [m]
L_{mold}	Length of mold [m]
L_{part}	Maximum length of molded part [m]
MFI	Plastic's melt flow index [g/min]
M_{mold}	Total mass of mold base [kg]
n_{cycles}	Number of molding cycles [–]
$n, \tau^*, D_1, D_2, D_3, A_1, A_3$	WLF model coefficients
n_{cavities}	Number of cavities in mold [–]
$n_{\text{cavities\_length}}$	Number of cavities in the length direction [–]
$n_{\text{cavities\_width}}$	Number of cavities in the width direction [–]
n_{cycles}	Total number of mold cycles that a mold is operated [–]
n_j	Number of j-th portions of mold cavity in mold [–]
n_{lines}	Number of cooling lines [–]

Variable	Meaning
n_{parts}	Total production quantity of parts to be molded [–]
P	Pressure [Pa]
P_{inject}	Pressure required to fill the cavity [Pa]
$Q_{molding}$	Total thermal energy of moldings [J]
$\dot{Q}_{line}$	Cooling power per cooling line [W]
$\dot{Q}_{molding}$	Cooling power [W]
r_v	Relative change in the specific volume [–]
R	Radius [m]
Re	Reynold's number [–]
$R_{finishing\_cost}$	Hourly cost of finishing [$/h]
$R^i_{finishing}$	Rate of finishing the part's surface in the manner i [m^2/h]
$R_{machining\_cost}$	Hourly rate of machining [$/h]
$R_{machining\_area}$	Rate of machining per unit area [m^2/h]
$R_{machining\_volume}$	Rate of machining per unit volume [m^3/h]
$R_{molding\_cost}$	Hourly cost of operating molding machine and operator if required [$/h]
R_W	Radius of curvature due to warpage [m]
s	Linear shrinkage rate [m/m]
$s_{\perp}$	Shrinkage rate perpendicular to flow [m/m]
$s_{//}$	Shrinkage rate parallel to flow [m/m]
s_{ave}	Average shrinkage rate [m/m]
t_c	Cooling time [s]
t_{cycle}	Cycle time of molding machine [s]
t_{insert_area}	Time required to machine the cavity surface area for one set of core and cavity inserts [h]
$t_{insert\_finishing}$	Time required to completely finish one set of core and cavity inserts [h]
$t_{insert\_machining}$	Time required to perform all machining for one set of core and cavity inserts [h]
t_{insert_volume}	Time required to machine the cavity volume for one set of core and cavity inserts [h]
t_p	Packing time before gate solidification [s]
$t_{residence}$	Residence time of the polymer melt [s]
T_c	Mold coolant temperature [°C]
T_e	Plastic's ejection temperature [°C]
T_g	Plastic's glass transition temperature [°C]

Variable	**Meaning**
T_{HDT}	Plastic's heat deflection temperature [°C]
T_{melt}	Melt temperature [°C]
T_{wall}	Mold wall temperature [°C]
v	Linear melt velocity [m/s]
$V_{inserts}$	Combined volume of one set of core and cavity inserts [m^3]
V_j	Volume of the *j*-th portion of mold cavity [m^3]
V_{part}	Volume of molded part [m^3]
$\dot{V}$	Volumetric flow rate [m^3/s]
W_{cavity}	Width of core and cavity inserts [m]
W_{cheek}	Distance from cavity side wall to side of mold [m]
W_{mold}	Width of mold [m]
W_{part}	Maximum width of molded part [m]
W_{pitch}	Distance between parallel cooling lines [m]