References

[1] Mahmoud, M. F. Material Selection for Engineering Design New York : Prentice Hall ,1997.

[2] Pigford, D.V. and Baur, G. Expert Systems for Business: Concepts and Application. 3 rd ed. Boston: Boyd & Fraser publishing company, 1995.

[3] Menges. G. and Mohren, P. How to Make Injection Molds. 2 rd. ed. Munich: Hanser Publishers, 1993.

[4] Mo Zhen, M. A Computer Aided Design Methodology for Plastic Injection Molding Design: A Case Study. Master's Thesis, Asian Institute of Technology, Thailand, 1996.

[5] Pacayamai, W. A classification and Coding System for Injection Mold Components. Master's Thesis, Department of Industrial Engineering, Chulalongkorn University, Thailand, 1987.

[6] Chang-Ho, L. A Knowledge-Based Systems Approach for Manufacturing Process Selection in Design (Design Engineers.) . Doctoral Dissertation, Department of Industrial Engineering, Ohio State University, U.S.A., 1992.

[7] Agrawal, S.K. Development of An Expert System for Opimum Gate Design. Master's Thesis, Department of Plastics Engineering, University of Lowell, 1992.

[8] Beiter, K.A. System Cost-Based Material Selection for Engineering Thermoplastics. Doctoral Dissertation, Department of Mechanical Engineering, Ohio State University, 1996.

[9] Stoeckhert, K. Mold-Making handbook for the Plastics Engineer Munich: Hanser Publishers, 1983.

[10] The Society of the Plastics Industry, Inc., Plastics Engineering Handbook , 5th ed. New York: Chapman & Hall, 1991.

[11] Mold Making & Mold design division and Southern California Section of the Society of Plastic Engineers . Mold Making Today and Tomorrow. : University Microfilms International A bell & Howell Company, Michigan, USA, 1989.

[12] The Japan Steel Works, Ltd. Injection Molding Machine Lessons: Basic Practice (n.p.)., 1993

[13] Wongsri, M. Expert System for Plastics Selection : Process Control Engineering Laboratory, Chemical engineering department, Chulalongkorn University, 1996.

[14] Scott, A.C. and Clayton, J.E.; Gibson, E.L. A practical Guide to Knowledge Aquisition New York: Addison-Wesley Publishing Co., 1991

[15] Hopgood, A. An Inference Mechanism for Selection. and its Application to Polymer. cited in Artificial Intelligence in Engineering. pp. 197-201, Vol. 4, No. 4, 1989.

[16] Dubios, J.H., and Pribble, W.J. Plastics mold Engineering Handbook New York : Van Nostrand Reinhold Co., 1978.

[17] Parasaei, H.R., and Jamshidi, M. Design and Implementation of Intelligent Manufacturing Systems New York: Prentice Hall, 1995.

[18] Scott, A.C., and Clayton J.E., and Gibson, E.L. A practical Guide to Knowledge Acquisition New York: Addison-Wesley, Publishing Co., 1991.

APPENDICES

APPENDIX A

The Knowledge of Materials Properties

Table A-1 Case-hardening that can be used universally.

AISI type	German Code	Material no.
P4	X 6 CrMo 4	1.2341
~ P2	21 MnCr 5	1.2162
P6	15 NiCr 14	1.2735
~ P21	X 19 NiCrMo 4	1.2764

Source : Stoekhert , K [9]

Table A-2 Common steel for maximum loading capacity

AISI type	German code	Material no.	Max. specific Surface pressure (N/mm^2)	Working hardness, HRC
~TF5	55 NiCr 10	1.2718	2000	56-58
L6	X 75 NiCrMo 5 3 3	1.2773	2800	60-62
D2	X 155 CrVMo 12 1	1.2379	3000	60-62

Source : Stoekhert , K [9]

Table A-3 Quenched and tempered tool steels with a low sulfur content

AISI-SAE type	German code	Material no.
P20	40 CrMnMo 7	1.2311
GF2	54 NiCrMo V 6	1.2711
SAE 4150	47 CrMo4	1.2332

Source : Stoekhert , K [9]

Table A-4 Steels with an increased sulfur content

AISI type	German code	Material no.
P20+S	40 CrMnMoS 8 6	1.2312
GF2+S	54 NiCrMoS 6	1.2708
H13+S	X 40 CrMoVS 5 1	1.2347

Source : Stockhert , K [9]

Table A-5 Fully hardening steels grades

AISI type	German Code	Material no.
-	X 45 NiCrMo 4	1.2767
H11	X 38 CrMo V 5 1	1.2343
02	100 MnCrW 4	1.2510
D2	X 155 CrVMo 12 1	1.2379
D3	X 210 Cr 12	1.2080

Source : Stockhert , K [9]

Table A-6 Summary of the most commonly used mold steels

AISI/SAE type	German code	Material no.	Description
P4	X 6 CrMo 4	1.2341	Case-hardening steel for hobbed cavities
~P2	21 MnCr 5	1.2162	Case-hardening steel for machined cavities
~P2	X 19 NiCrMo 4	1.2764	Case-hardening steel for machined cavities
-	14 CrMo V 6 9	1.7735	Nitriding steel, preferably for extruder barrels
-	34 CrAlMo 5	1.8507	Nitriding steel, preferably for extruder screws up to 70 in dia.
-	34 CrAlNi 7	1.8550	Nitriding steel, preferably for extruder barrels up to 250 in dia.
-	31 CrMo V 9	1.8519	Nitriding steel, preferably for extruder screws
P20	40 CrMnMo 7	1.2311	Heart-treated steel for photoetched cavities
P20+S	40 CrMnMo S 8 6	1.2312	Heart-treated steel with improved machining properties
H13+S	X 40CrMo VS 5 1	1.2347	Heart-treated steel with improved machining properties at Elevated working strength
-	X 45 NiCrMo 7	1.2767	Through-hardening steel with high toughness
H11	X 38 CrMo V 5 1	1.2343	Through-hardening steel with high retention to tempering for Nitriding
O1	100 MnCrW 4	1.2510	Meduum-alloyed mold steel with high close tolerance
D2	X 155 CrVMo 12 1	1.2379	Ledeburitic highly wear-resistant mold steel
D3	X 210 Cr 12	1.2080	Ledeburitic highly wear-resistant mold steel
420	X 42 Cr 13	1.2083	Corosion-resistant mold steel for normal corrosion attack
-	X 36 CrMo 17	1.2316	Corosion-resistant mold steel for high corrosion attack
18 MAR 300	X 3 NiCoMoTi 18 9 5	1.2709	Maraging steel, low distortion, suitable for nitriding
	PM steel		Special steel with highest wear-resistance properties

Source : Stoekhert , K [9]

Table A-7 Chemical properties of mold steel

													Typical	
AISI/SAE	German code	Material	Chemical composition										Hardness (HB) in condition as supplied	Tensie strength (N/mm^2) in condition as supplied
			C	Si	Mn	S	Cr	Mo	Ni	V	Co	Ti		
P4	X 6 CrMo 4	1.2341	0.07				3.8	0.5					max.120	max.360
~P2	21 MnCr 5	1.2162	0.21		1.3		1.2						max.210	max.710
~P2	X 19 NiCrMo 4	1.2764	0.19				1.3	0.2	4.1				max.250	max.850
-	14 CrMo V 6 9	1.7735	0.15		1.0		1.4	0.9		0.3			280-325	950-1100
-	34 CrAlMo 5	1.8507	0.34		0.7		1.2	0.2				Al 1.0	240-300	800-1000
-	34 CrAlNi 7	1.8550	0.34		0.5		1.7	0.2	1.0			Al 1.0	240-300	800-1000
-	31 CrMo V 9	1.8519	0.31		0.6		2.4	0.2		0.2			265-325	900-1000
P20	40 CrMnMo 7	1.2311	0.40		1.5		1.9	0.2					265-325	900-1000
P20+S	40 CrMnMo S 8 6	1.2312	0.40		1.5	0.1	2.0	0.2					265-325	900-1100
H13+S	X 40CrMo VS 5 1	1.2347	0.40	1.0		0.1	5.2	1.3		1.0			360-420	1200-1400
-	X 45 NiCrMo 7	1.2767	0.45				1.4	0.3	4.0				max. 250	max. 850
H11	X 38 CrMo V 5 1	1.2343	0.38	1.0			5.3	1.3		0.4			max. 240	max. 810
O1	100 MnCrW 4	1.2510	0.90		2.0		0.3			0.1			max. 220	max. 740
D2	X 155 CrVMo 12 1	1.2379	1.55				12.0	0.7		1.0			max. 250	max. 850
D3	X 210 Cr 12	1.2080	2.00				12.0						max. 250	max. 850
420	X 42 Cr 13	1.2083	0.40				13.0						max. 230	max. 780
-	X 36 CrMo 17	1.2316	0.36				16.5	1.2					max. 230	max. 780
18 MAR 300	X 3 NiCoMoTi 18 9 5	1.2709<	0.03					0.5	18.0		9.0	1.0	max. 320	max. 1080
	PM steel		0.06				3.0	3.0	Cu .5	Fe	Tic 33.0		max.400	max.1355

Source : Stockhert , K [9]

Table A-8 Case-hardening steels

AISI type	German Code	Mat. No.	Carbuizing (°C)	Inter-mediate annealing (°C)	Hardening (°C)	In	Surface hardness after quenching approx. HRC	Tempering (°C)
	Case-hardening steels							
P4	X 6 CrMo 4	1.2341	870-900	620-650	870-900	oil or hot bath	62	°C 100 200 300 400
						180-220 °C		HRC 62 60 57 54
~P2	21 MnCr 5	1.2162	870-900	620-650	810-840	oil or hot bath	62	°C 100 200 300 400
						180-220 °C		HRC 62 60 57 54
~P21	X 19 NiCrMo 4	1.2764	860-890	600-630	780-810	oil or hot bath	62	°C 100 200 300 400
						180-220 °C		After oil quencing 62 61 59 56
					800-830	Air	56	After air quenching 56 55 53 51

Source : Stoekhert . K [9]

Table A-9 Summary

AIS/SAE type	German code	Mat. No.	Hardening (°C)	In	Hardness after quenching approx. HRC	Tempering °C
	Heat-treated steels					
P20	40 CrMnMo 7	1.2311	840-870	Oil or hot bath 180-220 °C	51	°C 400 500 600 700 HRC 46 42 36 28
P20-S	40 CrMnMoS 8 6	1.2312	840-870	Oil or hot bath 180-220 °C	51	°C 400 500 600 700 HRC 46 42 36 28
	X 40 CrMoVS 5 1 H13+S	1.2347	1020-1050	Air , Oil or hot bath 500-550 °C	55	°C 400 500 600 700 HRC 55 50 50 32
	Full-hardening steels					
-	X 45 NiCrMo 4	1.2767	840-870	Air , Oil or hot bath 180-220 °C	56	°C 100 200 300 400 500 HRC 56 54 51 48 42
H11	X 38 CrMoV 5 1	1.2343	1000-1050	Air , Oil or hot bath 500-550 °C	55	°C 400 450 500 550 600 650 700 HRC 55 55 55,5 55 50 40 32
O1	100 MnCrW 4	1.2510	790-820	Oil or hot bath 180-220 °C	64	°C 100 200 300 400 500 HRC 64 61 56 50 45

Table A-9 (Cont') Summary

D2	X 155 CrVMo 12 1	1.2379	1000-1030	Oil , Air or hot bath	63	°C 100 200 300 400 500 525 550 600
				500-550 °C		HRC 64 61 58 58 59 60 58 50
	Special heat treatment		1040-1070	Oil , Air or hot bath	61	°C 100 200 300 400 500 525 550 600
				500-550 °C		HRC 61 60 58 59 62 62 58 51
D3	X 210 Cr 12	1.2080	940-970	Oil , Air or hot bath	64	°C 100 200 300 400
				500-550 °C		HRC 63 62 60 58
	Corrosion-resistant steels					
420	X 42 Cr 13	1.2083	1020-1050	Oil or hot bath	58	°C 100 200 300 400 500 525 550 600
				180-220 °C		HRC 58 57 54 53 53 54 52 39
-	X 36 CrMo 17	1.2316	1020-1050	Oil or hot bath	50	°C 100 200 300 400 500 525 550 600
				180-220 °C		HRC 50 47 46 46 47 47 42 32
	PM steel		960-980	Oil or hot bath	70	°C 100 200 300 400
				510 °C		HRC 70 69 68 62

Source : Stoekhert , K [9]

Table A-10 Common Methods of surface treatment.

Method	Treatment temp. (°C)	Required properties of the tool steels	Thickness of layer	Surface hardness (HV)
Carburizing	900-1000	Low C contant, insensitivity to overheating	Up to 2 mm	max. 900
Oxidizing	300-550	Retention of tempering, degreased surface	Up to 0.01 mm	-
Nitriding	470-570	Good tempering properties harden resp. tempered condition (depassivated surface)	Up to 1 mm	max. 1200
Boronizing	800-1050	Insensitivity to overheating, Si-content as low as possible	Up to 0.4 mm.	max. 2000
TIC or TiN coatings	> 900	Insensitivity to overheating, metalic bright surface	6-9 μm	max. 4800
Spark deposition	Probably several thousand	None	Up to 0.1 mm	approx. 950
Hard chromium plating and nickel plating	50-70	Cr content as low as possible , depassivated surface	Up to 1 mm	1000-1200

Source : Stoekhert , K [9]

Table A-11 Summary

Steel grade , AISI type	German code	Mat No.	Coefficient of thermal expansion $\frac{10\ m}{m \times {}^{\circ}C}$ 20-100	20-200	20-300	20-400 °C	Thermal Conductivity $\frac{J}{cm \times s \times {}^{\circ}C}$ 20	350	700 °C
P4	X 6 CrMo 4	1.2341	12.0	12.3	12.7	13.2	0.392	0.365	0.335
~P2	21 MnCr 5	1.2162	12.2	12.9	13.5	13.9	0.395	0.365	0.335
~P21	X 19 NiCrMo 4	1.2764	10.4	11.4	12.2	12.7	0.335	0.322	0.320
-	14 CrMoV 6 9	1.7735	11.2	11.8	12.5	13.0	0.371	0.365	0.342
-	31 CrMoV 9	1.8519	11.8	12.5	12.9	13.4	0.364	0.337	0.317
P20	40 CrMnMo 7	1.2311	11.1	12.9	13.4	13.8	0.357	0.334	0.320
P20-S	40 CrMnMos 8 6	1.2312	11.1	12.9	13.4	13.8	0.375	0.334	0.320
H13-S	X 40 CrMoVS 51	1.2347	10.1	10.3	10.6	11.2	0.245	0.272	0.292
-	X 45 NiCrMo 4	1.2767	12.3	13.1	13.3	13.8	0.288	0.298	0.305
H11	X 38 CrMoV 5 1	1.2343	10.0	10.2	10.5	11.1	0.253	0.272	0.305
02	90 MnCrV 8	1.2842	10.4	12.2	13.0	13.6	0.342	0.330	0.318
D2	X 155 CrVMo 12 1	1.2379	10.5	11.5	11.9	12.2	0.167	0.205	0.242
D3	X 210 Cr 12	1.2080	10.4	11.6	12.4	12.6	0.167	0.208	0.245
420	X 42 Cr 13	1.2083	10.5	11.0	11.0	11.5	0.200	0.230	0.262
-	X 36 CrMo 17	1.2316	10.5	11.0	11.0	12.0	0.172	0.210	0.247
18 MAR	X 3 NiCoMoTi 18 9 5	12.709	10.2	10.2	10.5	10.9	0.048	0.057	0.076
	PM steel	300	10.0	10.2	10.5	10.9	0.048	0.057	0.076

Source : Stoekhert , K [9]

Table A-12 Technical data of beryllium-copper alloys

Designation	C 17 200	C 17 300	C 17 000	C 17 510	C 17 500
Composition	Be 1.80-2.00%, Co/Ni 0.2% min., Co/Ni/Fe 0.6% max., Cu balance	Be 1.80-2.00%, Co/Ni 0.2% min., Co/Ni/Fe 0.6% max., Pb 0.20-0.60% Cu balance	Be 1.60-1.79%, Co/Ni 0.2% min., Co/Ni/Fe 0.6% max., Cubalance	Be 0.20-0.60%, Ni 1.40-2.20% Cu balance	Be 0.40-0.75%, Co 2.40-2.70%, Cu balance
Density Kg/m^3	8250		8415	8610	8775
Therm.conductivity W / (m.K)	130		130	260	260
Therm.expansion 10^{-6} K^{-1}	17.5		17.5	17.6	18
Specific heat capacity J/ (kg.K)	420		420	420	420
Electric resistivity 10^{-8} Ω.m	7.7		7.7	3.8	3.8
Modulus elasticity GPa	131		128	138	138
Tensile strength [Mpa]	I 415-585 II 620-895 III 1140-1310 IV 1275-1480		I 415-585 II 620-895 III 1035-1310 IV 1170-1450	I 240-380 II 450-550 III 690-830 IV 760-900	
Yield strength [MPa]	I 140-415 II 515-725 III 1000-1200 IV 1140-1380		I 140-205 II 515-725 III 860-1070 IV 930-1140	I 140-310 II 340-515 III 550-690 IV 690-830	

Table A-12 (Cont') Technical data of beryllium-copper alloys

Elongation [%]	I 35-60 II 10-20 III 1000-1200 IV 1140-1380	I 35-60 II 10-20 III 4-10 IV 2-5	I 20-35 II 10-15 III 10-25 IV 10-20	
Rockwell hardness	I B45-80 II B88-103 III C36-41 IV C39-44	I B45-85 II B91-103 III C32-39 IV C35-41	I B25-50 II B60-75 III B92-100 IV B95-102	

Notes : I : Solution heart treated

II : Cold drawn

III : Solution heat treated and age hardened

IV : Cold drawn and age hardened

Source : Menges, G , Mohren, P. [7]

Table A-13 Aluminum Alloys for injection molds

A.A. No.	7075-T6	7029-T6
Composition	Al, Zn, Mg, Cu, Cr	Al, Zn, Mg, Cu
Treatment	Solution treated Artificially aged	Solution treated, Artificially aged
Density kg / dm^3	2.80	2.74
Coefficient of thermal expansion	2.33×10^{-6}	24.7×10^{-6}
Thermal conductivity W / (kg.m)	140	126
Ultimate tensile strength MPa	572	537
Yield strength MPa	503	469
Brinell hardness BHN	150	125

Source : Menges, G , Mohren, P. [7]

Table A-14 Steels for injection Molds

Steel AISI	Application
P20	Suitable for all types and sizes of machine-cut molds. Usually used in the prehardened condition Rockwell "C" 32 to 35. This should be carburized and hardened for low viscosity or glass filled plastics and for usage in excess of 100,000 pcs per cavity
H13	Used for large and small molds when toughness and strength is required. Good dimensional stability during hardening. Hardens up to Rockwell "C" 52 but is tougher at "C" 48
A2	For small and medium size molds when higher hardness is required as for molding abrasive materials.
D2	For small molds when abrasion becomes a problem. Also for molds operating at temperatures up to 750 ^{o}F
Type 420 Stainless	For small and large molds for molding corrosive resins, such as PVC and Delrin. Also used when rusting is problem because of "sweating" of mold surface. Heat treat precautions: after hardening, double temper at 750 ^{o}F for highest toughness and best corrosion resistance. Hardness will be Rockwell "C" 48 to 52
SAE 4140	Usually used for holders and shoes. Can be used for molds where a high finish is not necessary. Usually used in the prehardened condition Rockwell "C" 28 to 32
M2 High Speed Steel	Use if operating temperatures are above 1000 ^{o}F, but not higher than 1150 ^{o}F, and the mold hardness must be higher than 60 Rc.

Source : DuBias, J.H. & Pribble, W.I, VAN NOSTRAND company 1978 . [16]

Table A-15 Beryllium Copper Alloys Properties and Applications.

Composition	Berylco Copper Alloy Ingot	Density , Lb / cu in.	Thermal Cond. BTU/sq ft/in./ hr /°F (68°F)	Rockwell Hardness[a]	Pouring Range, °F	Characteristics and Applications
Be 0.45-0.75 Co 2.35-2.70	10C	0.311	1400-1600	B 40 ; B96	2050-2250	High thermal and electrical conductivity, good strength and good high temperature properties. Ideal for high temperature, lower pressures, and maximum cooling or heating properties.
Be 1.65-1.75 Co 0.20-0.30	165C	0.298	790-900	B 59; C 38	1900-2050	High strength and hardness, with good resistance to corrosion. Recommended for salt water immersed applications.
Be 1.90-2.15 Co 0.35-0.65 Si 0.20-0.35	20C	0.292	650-800	B 63 C 43	1850-2050	High strength, hardness and excellent fluidity. Ideal for investment, sand and ceramic castings. Good thermal properties (2-3 times steel)
Be 2.25-2.45 Co 0.35-0.65 Si 0.20-0.35	245C	0.292	600-750	B 75; C 45	1850-2000	High strength, hardness and wear resistance with good thermal conductivity. Applicable to pressure casting, sand and ceramic castings, very high fluidity.
Be 2.50-2.75 Co 0.35-0.65 Si 0.20-0.35	275C	0.292	600-750	B 85; C 46	1850-1975	Very high castability, or fluidity, hardness and wear resistance with good thermal conductivity. For pressure cast molds, sand and ceramic casting.

[a] Values for solution heat treated before semicolon; solution heat treated and aged after.

Source : DuBias, J.H. & Pribble, W.I, VAN NOSTRAND company 1978 . [16]

Table A-16 Through-hardening steels

Abbreviation	Materials No.	Strength N/mm^2 or Hardness Rockwell C	Remark
X38CrMoV5 1	1.2343	1450	standard hot work steel
X45NiCrMo4	1.2767	50-54	Very good polishability, high toughness
90MnCrV8	1.2842	56-62	Normal wear resistance
X155CrVmO121	1.2379	58	Good wear resistance, good toughness
X210 Cr12	1.2080	60-62	High wear resistance
X165CrMoV12	1.2601	63	Highly wear resistance steel

Source : Menges, G , Mohren, P. [7]

Table A-17 Through-hardening steels

Abbreviation	Materials No.	Strength N/mm^2 or Hardness Rockwell C	Remark
X42Cr13	1.2083	54-56	Corrosion-resistance only when polished
X36CrMo17	1.2316	50	Machining after heat treatment, high corrosion resistance
X105CrMo17	1.4125	57-60	Rust-and acid-resistance, wear-resistance

Appendix B

Example of Interview Test Question

1. What 's type of steel used to make injection mold for PVC pipe?

   Answer...................... true..........false.........

2. Please tell me the type of steel or some steel grade used to make injection mold.

   Answer...................... true..........false.........

3. What information do AISI -SAE, German code, Materials No. provide ?

   Answer...................... true..........false.........

4. Please tell me how can we increase hardness of steel ?

   Answer...................... true..........false.........

5. What is the benefit of high thermal conductivity materials in mold making?

   Answer...................... true..........false.........

6. What is RC, V unit in metal table ?

   Answer...................... true..........false.........

Appendix C

Table C-1 Physical Properties of HPDE

Physical Properties	
Specific gravity (g/cm^3)	0.96
Thermal conductivity (Btu / ft^2/ hr/(^oF/ ft)	0.19
Coefficient of thermal expansion (in/in/$^oF x10^{-3}$)	7
Specific heat (Btu/lb/^oF)	0.54
Water absorption (24 hr) , (%)	0.02
Flammability	Burns
Mechanical Properties	
Tensile strength (1000 Psi)	3.5-5.0
Compressive strength (1000 Psi)	-
Flexural strength (1000 Psi)	-
Impact strength (ft-lb/in)	8-10
Modules of elasticity in tension (10^5 Psi)	0.9-1.2
Hardness-Rockwell	R30-56
Elongation (%)	100-400

Source : Mo Zhen [4]

Table C-2 Chemical Properties of HDPE

Polymer	Melt Temp. (^oC)	Specific Heat (Kj/Kg/OC)	Latent heat (Kj/Kg)	Crystallity (%)	Heat Required (Kj/Kg)
LDPE	190-220	2.30	150	50	489
HDPE	210-240	2.30	209	80	627

Source : Mo Zhen [4]

Biography

Komet Poempoonchokkana was borned on 28 march 1975. He was graduated from Faculty of Engineering, Chulalongkorn University and received a bachelor degree in mechanical engineering in 1997. In 1998, he admitted to study at The Regional Centre for Manufacturing Systems Engineering in the Master Degree Program of Engineering in Engineering Managemnent, co-operating with Chulalongkorn University, Thailand and University of Warwick, England.