

特殊模具鋼應用於金屬粉末射出成型
Tool Steels for the M.I.M Tooling System

梧濟工業股份有限公司

商智苑

- M. I. M合金粉末特性分類
- M. I. M模具失效分析與對策
- M. I. M模具材料特性與運用
- M. I. M模具系統應力分佈概念
- M. I. M模具表面處理之建議

Selected Mechanical Properties of PIM Metals and Alloys (HT=heat treated)

| Material | Composition, wt. % | Density % | Yield Strength Rp0.2 | UTS Mpa | Elongation % | Hardness | 模具失效狀態 |
|------------------------|--------------------------------|-----------|----------------------|---------|--------------|----------|-----------|
| 1020 steel | Fe-0.2C | 96 | 185 | 380 | 23 | - | 刮損磨耗與疲勞 |
| 4140 | Fe-1Cr-0.4C | 97 | 390 | 580 | 15 | 18 HRC | |
| 4140 (HT) | Fe-1Cr-0.4C | 93 | 1240 | 1380 | 2 | 40 HRC | |
| 4340 steel(HT) | Fe-2Cr-1Ni-1Mn-0.4C | 96 | 480 | 620 | 6 | 20 HRC | |
| 4640 steel (HT) | Fe-2Ni-1Mo-0.4C | 97 | 1400 | 2000 | 3 | 30 HRC | |
| gold, 18 ct. | 75Au-12.5Ag-12.5Cu | 75 | 108 | 147 | 1 | 66 HRB | 粘著磨耗與疲勞裂痕 |
| hastelloy | Ni-28Mo-2Fe | 97 | 350 | 800 | 40 | 30 HRC | |
| inconel 718 (HT) | Ni-19Cr-18Fe-5Nb-3Mo-1Ti-0.4Al | 100 | 1130 | 1330 | 14 | - | |
| invar | Fe-36Ni | 98 | 240 | 425 | 40 | 65 HRB | |
| iron | Fe | 96 | 105 | 220 | 35 | 50 HRF | |
| iron-copper steel | Fe-2Cu-0.8C | 95 | - | 700 | 10 | 92 HRB | |
| iron-chromium steel | Fe-1Cr-0.5C | 94 | - | 600 | 10 | 90 HRB | |
| iron-molybdenum | Fe-5Mo | 98 | 210 | 410 | 34 | 66 HRB | |
| iron-nickel | Fe-2Ni | 96 | 190 | 345 | 30 | 55 HRB | |
| iron-nickel | Fe-8Ni | 96 | 255 | 440 | 24 | 75 HRB | |
| iron-nickel | Fe-50Ni | 96 | 170 | 420 | 20 | 50 HRB | |
| iron-nickel steel | Fe-2Ni-0.5C | 94 | 215 | 450 | 20 | 75 HRB | |
| iron-nickel steel (HT) | Fe-2Ni-0.5C | 94 | 1230 | 1230 | 1 | 45 HRC | |
| iron-nickel steel | Fe-2Ni-0.9C | 96 | 450 | 650 | 9 | 90 HRB | |
| iron-nickel steel (HT) | Fe-7Ni-0.5C | 95 | 1420 | 1460 | 1 | 46 HRC | |

M.I.M合金粉末特性分類

梧濟工業

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|------------------------|----------------------|--------------|----------------------------|------------|------------------|----------|--------------------|
| iron-phosphorus | Fe-0.6P | 99 | 260 | 280 | 2 | 80 HRB | 磨耗磨耗 |
| iron-silicon | Fe-3Si | 99 | 345 | 520 | 25 | 85 HRB | |
| iron-silicon | Fe-6.5Si | 99 | - | 375 | 0 | 37 HRC | |
| kovar or F15 | Fe-29Ni-17Co | 98 | 350 | 520 | 42 | 60 HRB | 粘著磨耗 潤磨氧化 反應 |
| nickel-iron | Ni-20Fe | 91 | - | 470 | 31 | 53 HRB | |
| niobium superalloy | Nb-10W-10Ta | 98 | 315 | 440 | 25 | 20 HRC | |
| stainless 17-4 PH | Fe-16Cr-4Ni-4Cu | 96 | 750 | 900 | 10 | 25 HRC | |
| stainless 17-4 PH (HT) | Fe-16Cr-4Ni-4Cu | 96 | 965 | 1140 | 12 | 35 HRC | |
| stainless 304L | Fe-18Cr-8Ni | 97 | 240 | 480 | 35 | 85 HRB | |
| stainless 316L | Fe-17Cr-12Ni-2Mo-2Mn | 96 | 220 | 510 | 45 | 75 HRB | |
| stainless 316L duplex | Fe-21Cr-9Ni-3Mo-2Mn | 95 | 230 | 540 | 43 | 80 HRB | |
| stainless 410L (HT) | Fe-11Cr-0.5C | 95 | 410 | 650 | 5 | 20 HRC | |
| stainless 420 (HT) | Fe-13Cr-1Mn-1Si | 92 | 690 | 1440 | 6 | 47 HRC | |
| stainless 430 | Fe-17Cr-1Mn-1Si-1Ni | 93 | 230 | 390 | 25 | 68 HRB | |
| stainless 440C (HT) | Fe-17Cr-1Ni-1C | 96 | 410 | 620 | 2 | 43 HRC | |

M.I.M合金粉末特性分類

梧濟工業

Selected Mechanical Properties of PIM Metals and Alloys (HT=heat treated)

| Material | Composition,wt.% | Density % | Yield Strength Rp0.2 | UTS Mpa | Elonga- tion% | Hardness | 模具失效 狀態 |
|----------------------|--------------------------|--------------|----------------------------|------------|------------------|----------|------------|
| stellite | Co-28Cr-4W-3Ni-1C | 99 | - | 1020 | 3 | 40 HRC | 粘著磨損 |
| super invar | Fe-32Ni-5Co | 96 | 285 | 440 | 40 | 65 HRB | |
| titanium | Ti | 95 | 1100 | 1300 | 16 | - | |
| Ti-6-4 | Ti-6Al-4V | 98 | 800 | 880 | 12 | 35 HRC | |
| tool steel | Fe-6W-5Mo-4Cr-2V-1C | 99 | - | 2000 | 0 | 66 HRC | 磨粒磨耗 |
| tungsten heavy alloy | W-8Mo-8Ni-2Fe | 100 | - | 1115 | 20 | - | |
| tungsten heavy alloy | W-5Ni-2Cu | 98 | 900 | 1050 | 10 | 35 HRC | |
| tungsten heavy alloy | W-4Ni-1Fe | 99 | 650 | 1000 | 20 | 50 HRA | |
| tungsten heavy alloy | W-5Ni-2Fe | 100 | 660 | 930 | 30 | 25 HRC | |
| udimt 700 | Ni-18Co-15Cr-5Mo-4Al-3Ti | 100 | 910 | 1340 | 14 | - | 粘著磨耗 |

M.I.M合金粉末特性分類

梧濟工業

工具鋼基地機械特性

Wear resistance

耐磨性

Toughness

韌性

Compressive strength

抗壓強度

Retention of hardness

硬度維持能力

M.I.M 模具失效分析與對策

梧濟工業

模具典型失效狀態

A

Abrasive Wear

Erosion of the Matrix

B

Adhesive Wear

Local Friction Bonding,
Material Transfer

C

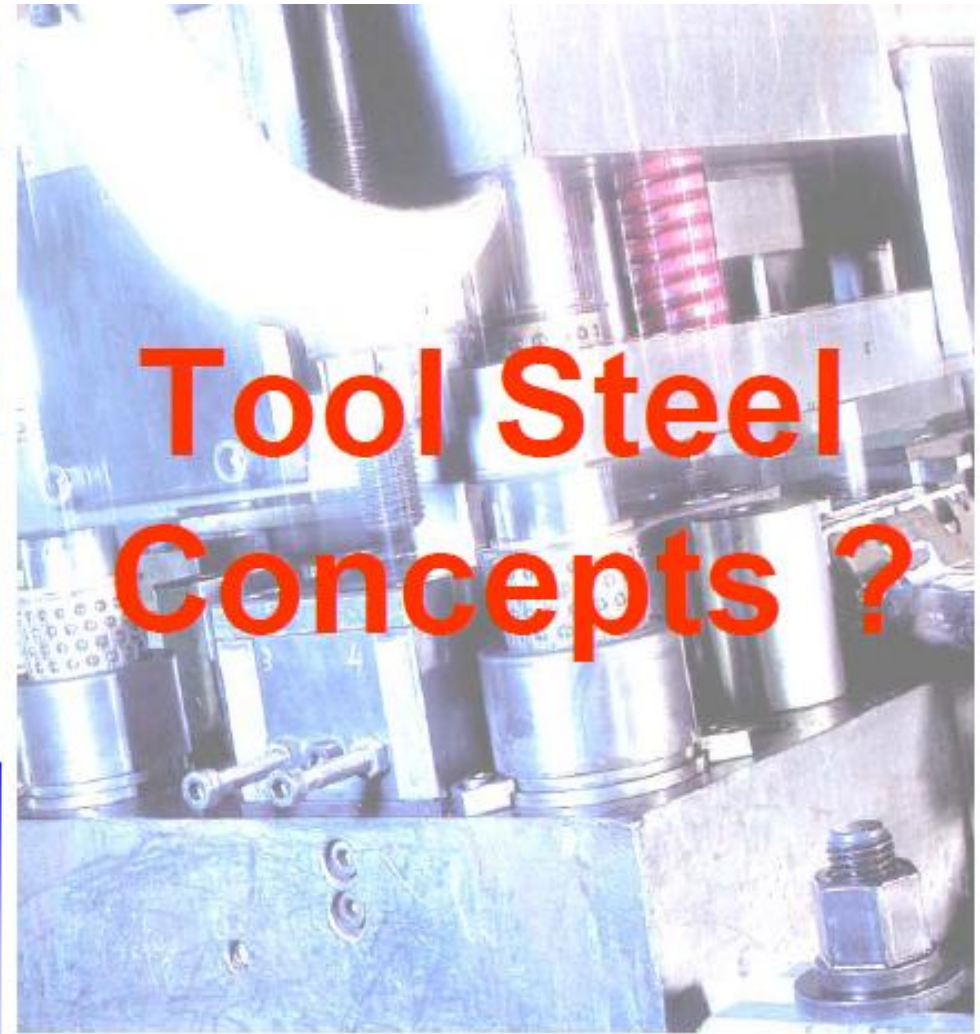
Fatigue

Surface Delamination,
Plastic Deformation → Fatigue
Crack Propagation

D

Tribooxidation

Chemical Reaction
Tool - Workpiece
Lubricant / Coolant



M.I.M 模具失效分析與對策

梧濟工業

Alloying Concept 合金設計概念

Wear Resistance
耐磨性

粉末冶金製程
Powder Metallurgy

ESR/PESR

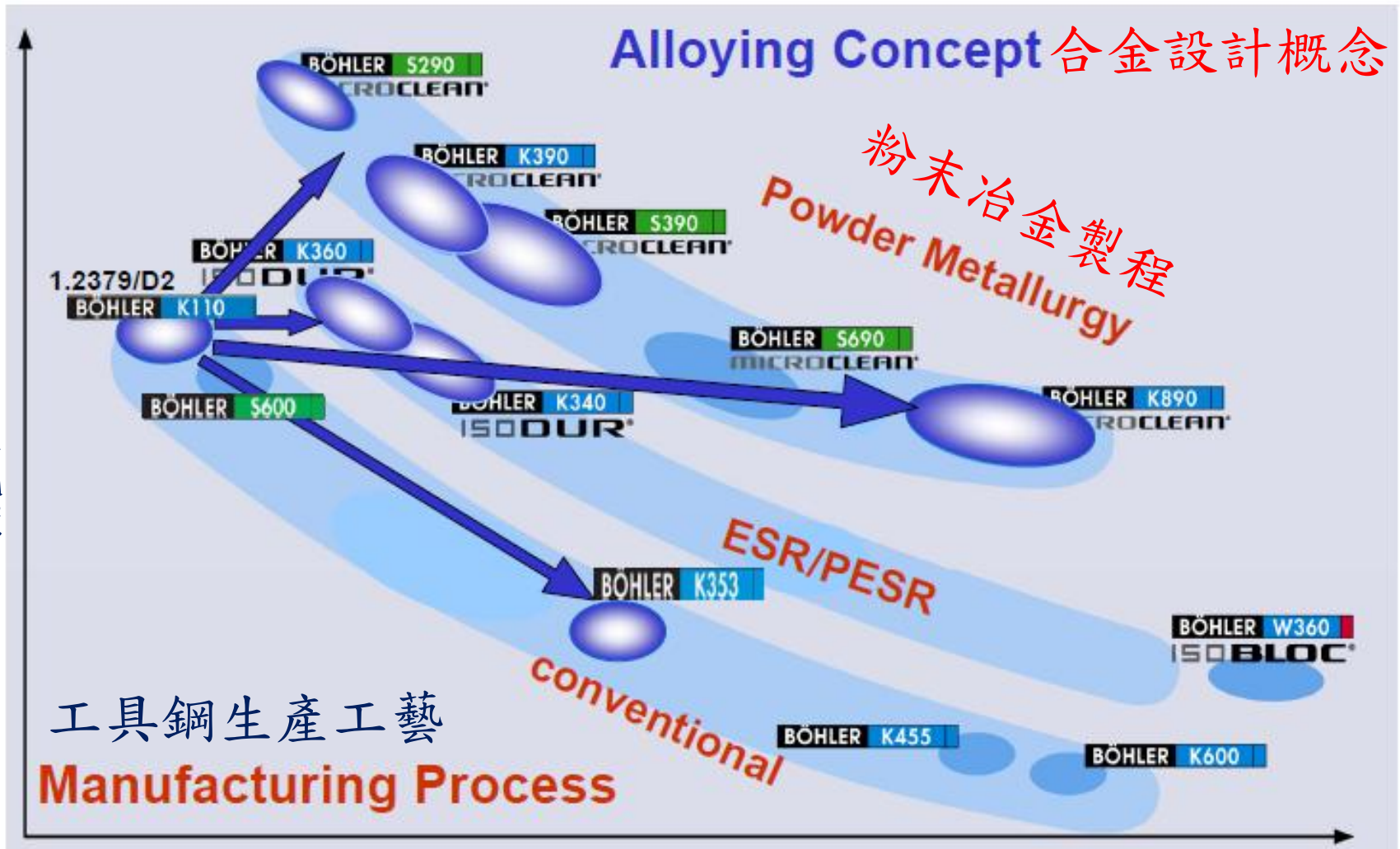
conventional

工具鋼生產工藝
Manufacturing Process

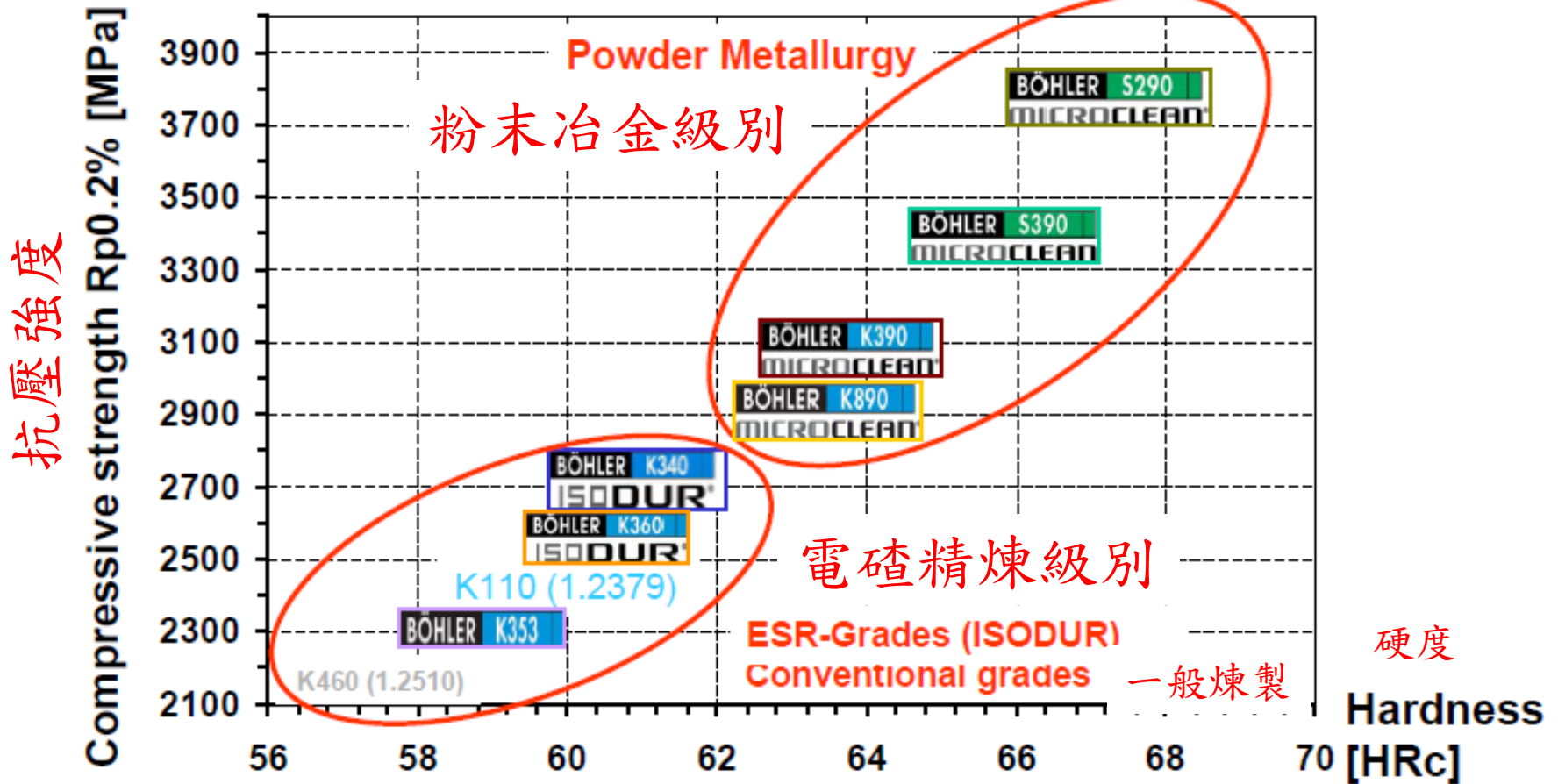
Toughness / Ductility
韌性與延展性

M.I.M 模具材料特性與選用

梧濟工業



Compressive strength of tool steels in acc. to DIN 50106 Cylindrical sample with a Height/Diameter ratio of 1.5



M.I.M 模具材料特性與選用

梧濟工業

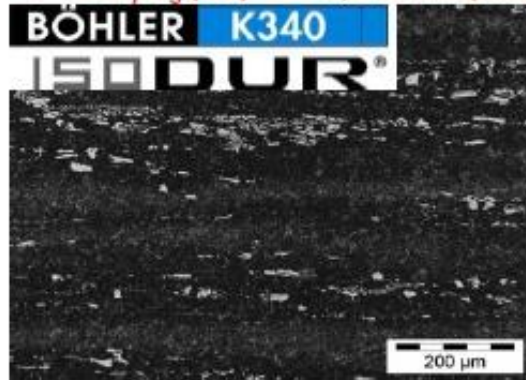
碳化物的種類與碳化物分佈



~ 11 % M_7C_3 (Cr) + ~ 1% MC(Nb)

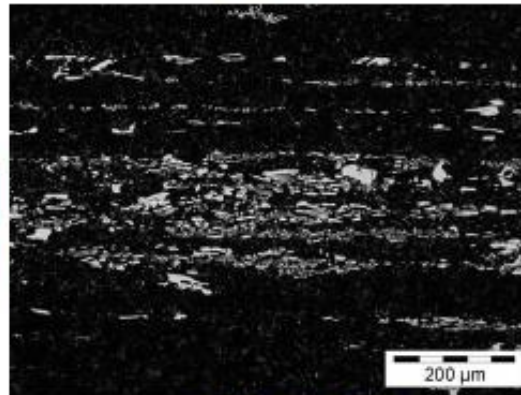
8 % Cr-Grades

~ 7 % M_7C_3 (Cr) + ~ 0,5% MC(Nb)

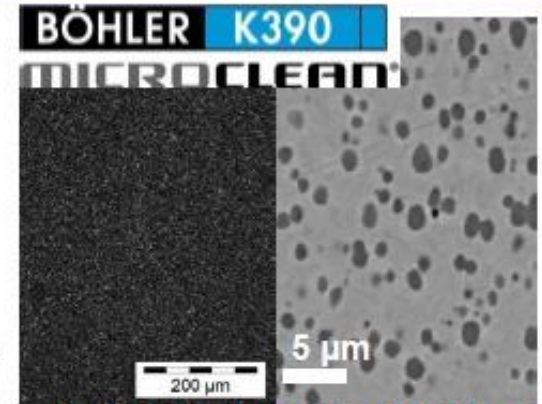


12 % Cr-Grades

K110
1.2379/D2



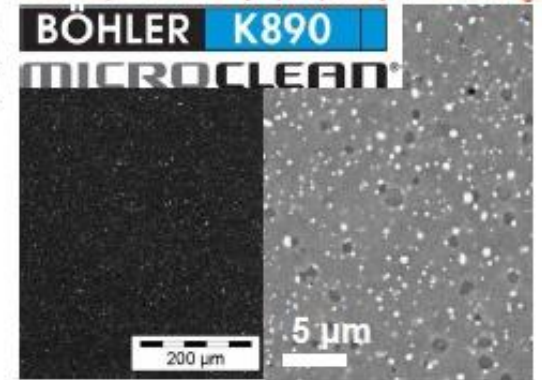
ca. 15 % M_7C_3 (Cr)



ca. 16 bis 17 % MC (V,W,Mo)

PM - Grades

ca. 2,5% MC (V,W,Mo) + 6% M_6C



M.I.M金屬粉末射出模具系統

2-1

M.I.M複雜零件



Fig. 5.1: Collection of MIM parts showing shape complexity
(Courtesy of BASF)

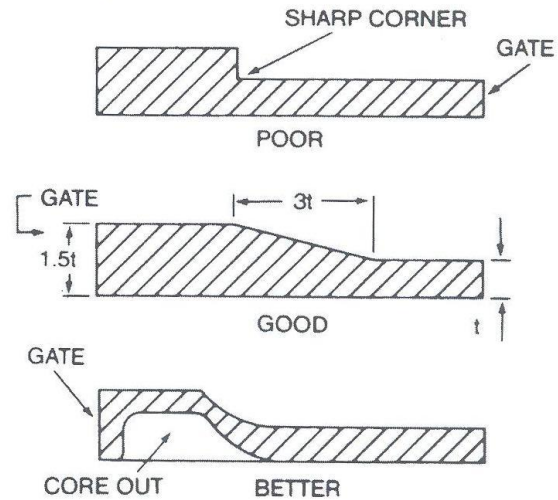
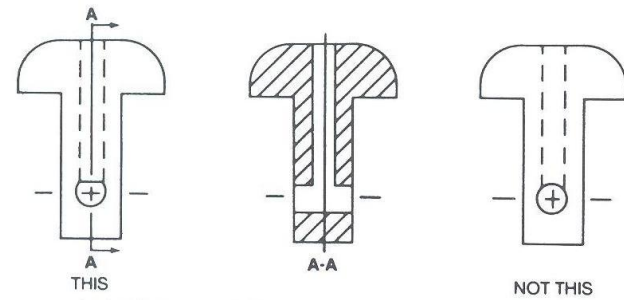
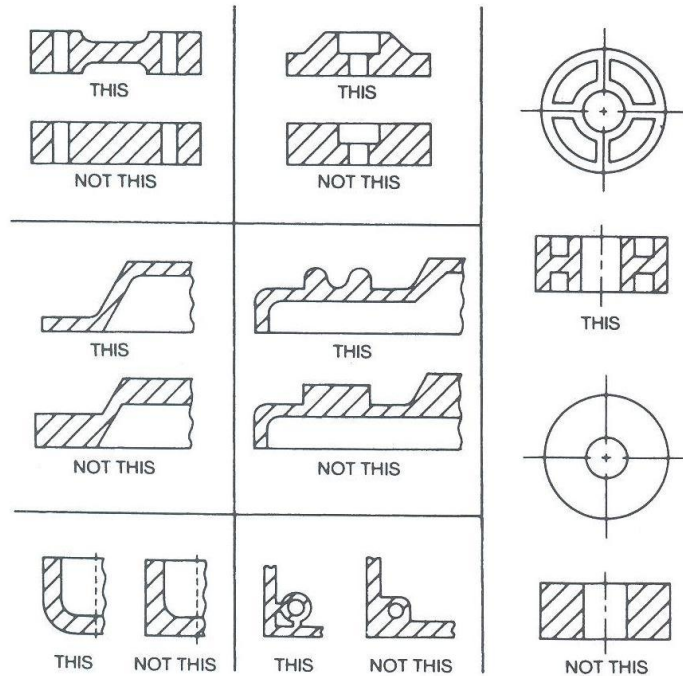
M.I.M模具統應力分佈概念

梧濟工業

2-2減少應力集中之設計之模具設計重點

1. 肉厚斷差不要太大，厚壁小於10mm
2. 最大肉厚極限在30mm(較有經濟性與高良率)
3. 內孔不要有倒角設計
4. R角不得小於0.4~0.8mm
5. 邊角至少大於0.075mm
6. 拔模斜角 $>2^\circ$
7. 零件最小孔徑0.1mm

2-2減少應力集中之設計之模具設計重點



粉末進料口位置

粉末送料最好由模內型腔肉厚處經肉薄處流動，反之，如進料口由型腔肉薄處往肉厚處流動，易導致應力集中，阻流(Sink-marks)及流道線殘留在零件表面，尤其在一模多穴的型腔設計更要注意分流道與入料口的位置與尺寸。

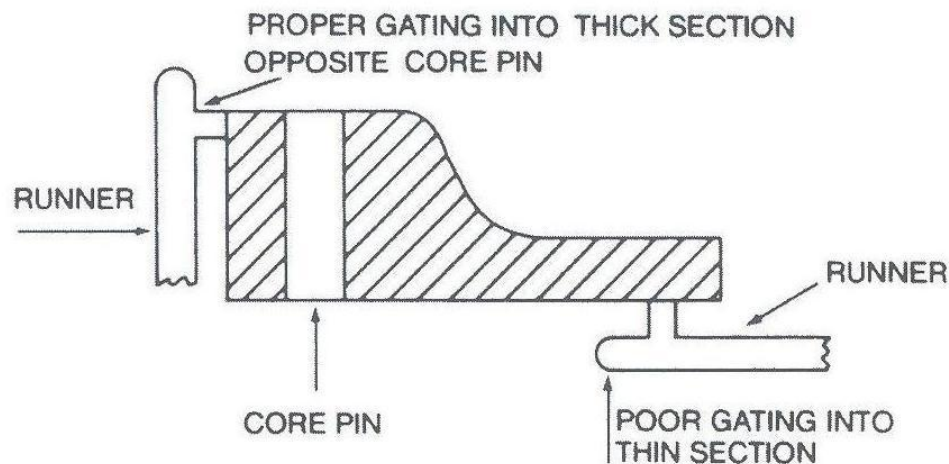


Fig. 5.5: Gate location
(From 'Metal Powder Report', November-1991)

外螺牙之合模線

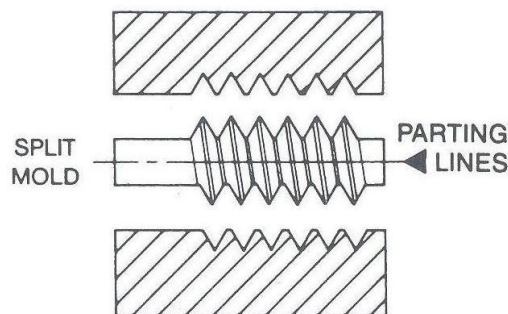


Fig. 5.6: Moulding external threads
(From 'Metal Powder Report', November 1991)

一般外螺牙與內螺牙均可用M.I.M成型，但內螺牙之成型會採用螺牙型心軸退牙機構設計，但涉及到

1. 螺牙型心之拉力強度韌性與螺紋加工精度，面粗度均影響其壽命。
2. 機械設計與模具結構成本高。

故一般採用成型後攻牙加工(Topping)

M.I.M零件尺寸公差與模具精度

| M.I.M零件尺寸 | 零件允許公差 | 模具公差 | 所需模座硬度 | 模座材質 Buderus |
|-----------|----------------|--------------|-----------|-----------------|
| <3mm | ±0.05mm | 0.005-0.01mm | HRC:50~52 | 1.2344 |
| 3~0mm | ±0.06mm | 0.005-0.01mm | HRC:50~52 | 1.2344 |
| 6~15mm | ±0.075mm | 0.008-0.01mm | HRC:48~52 | 1.2344 |
| 15~30mm | ±0.15mm | 0.008-0.01mm | HRC:48~52 | 1.2344 |
| 30~60mm | ±0.25mm | 0.008-0.02mm | HRC:48~52 | 1.2344 |
| >60mm | ±0.5% 之零件尺寸 | 0.01-0.02mm | HRC:44~46 | 1.2344 |

M.I.M模穴應力分佈

應力集中位置比較

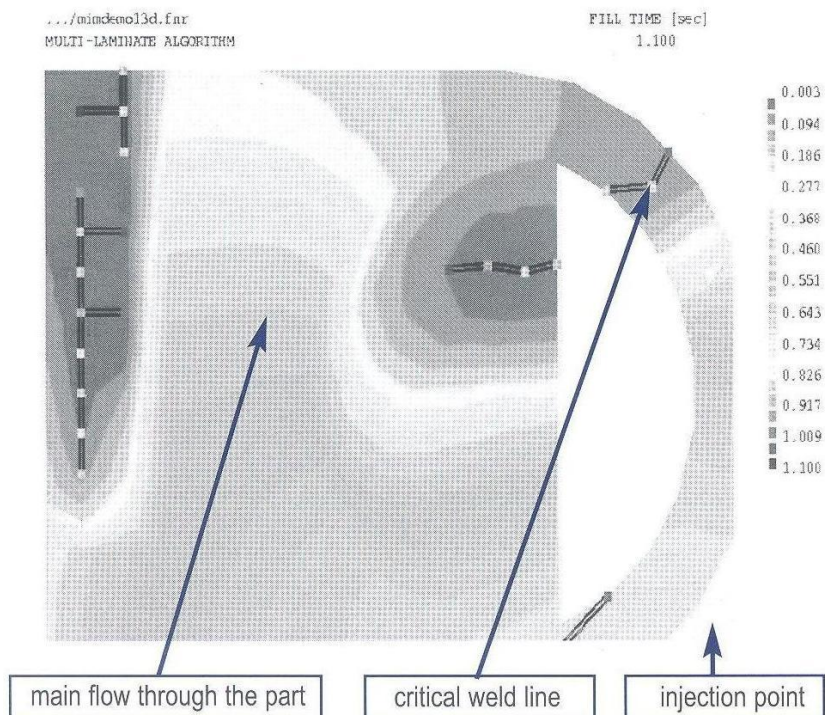


Fig. 5.7: Moldflow[®] simulation of mould filling with critical position of weld line (Courtesy of IFAM)

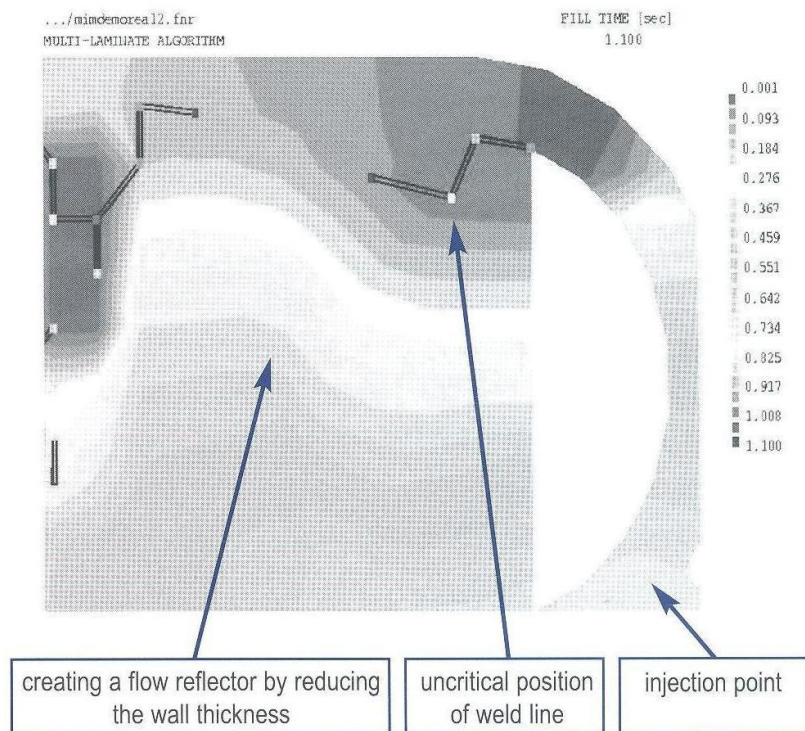


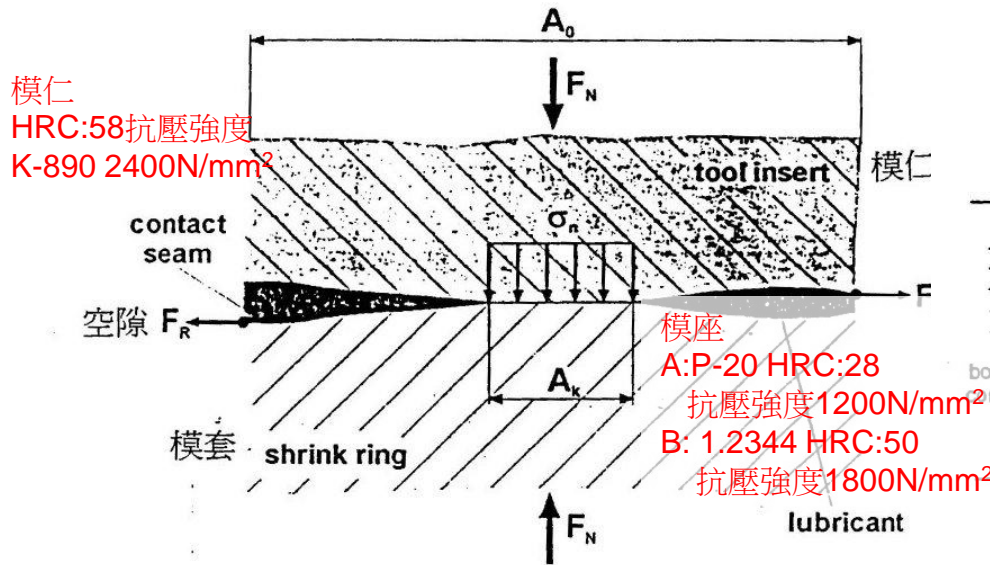
Fig. 5.8: Optimized geometry with improved mould filling and uncritical position of weld line (Courtesy of IFAM)

模具型腔與模座接觸面積

contact area are written as A_k and A_0 respectively, so the RCA is given as:

$$RCA = \frac{A_k}{A_0} \quad \left(\begin{array}{l} \text{實際接觸面} \\ \text{(受力時暫態接觸面)} \end{array} \right) \quad \left(\begin{array}{l} \text{未受力時總接觸面} \end{array} \right)$$

兩接觸面一方有彈性變形，導致另一接觸面錯位差排現象



兩金屬面在受力狀態，瞬間產生隙縫

Figure 5. Contact seam between two metallic parts under pressure.

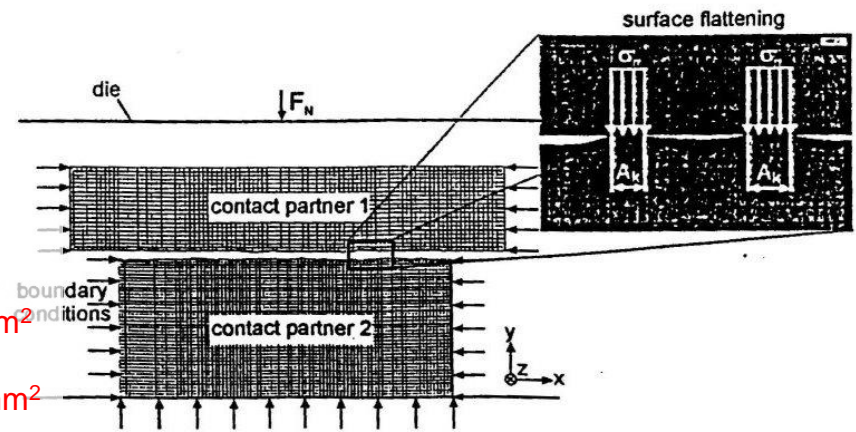


Figure 9. FE-simulation of the contact between two rough surfaces (2D).

M.I.M 模具統應力分佈概念

梧濟工業

模仁(型腔)與模座抗壓強度之比較

Case study A 高強度，尺寸精度維持時間長

| 模具組件 | Bö hler | 硬度(HRC) | 抗壓強度 | 材料特性 |
|------|-------------------------|-------------------------|--------------------------------|-------------------|
| 型腔材料 | K-390 K-490 K-890 | 60-62 56-58 54-56 | 2800~3000 N/mm ² | 高尺寸穩定性 高耐粘著磨耗性 |
| 模框 | W-360 | 54-56 | 2400N/mm ² | 高尺寸穩定性 |
| 模座 | Buderus 2344 ISO-B | 50-52 | 1800N/mm ² | 高韌性 高疲勞強度 |

模仁(型腔)與模座抗壓強度之比較

Case study B: 模座易變形導致模仁破裂

| 模具組件 | Bö hler | 硬度(HRC) | 抗壓強度 | 材料特性 |
|------|-------------------------|-------------------------|--------------------------------|-------------|
| 型腔材料 | K-390 K-890 K-490 | 60-62 56-58 54-56 | 2800~3000 N/mm ² | 高耐磨性 高硬度 |
| 模框 | P-20 1.2311 | 22-24 | 800~1000 N/mm ² | 易切削 低強度 |
| 模座 | P-3,P-5 1050碳鋼 | 18-20 | 600~800 N/mm ² | 易切削 易變形 |

模具表面鍍層對磨擦係數的影響

| M.I.M粉末種類 | 磨耗機構 | 建議鍍層 |
|----------------------------|--------------|-----------------------------|
| 含Ni, Ti, Al, Cu,Cr不銹鋼系,鈦合金 | 粘著磨耗 | DLC, (WC/C),CrN |
| 含Fe, Co,工具鋼粉,高速鋼粉 | 磨粒磨耗 刮損磨耗 | TiC, TiCN, SiAlON, TiAlN |

Comparison of coefficients of friction and wear of different deposits 不同表面鍍層對摩擦係數與磨耗機構的比較

| Deposit 表面鍍層種類 | Process of Deposition 鍍層方式 | Coef. Friction 摩擦係數 | Wear : mm ³ /N*m10 ⁻⁹ 磨耗量 | Wear Resistance Indication 耐磨指數 |
|-------------------|-------------------------------|------------------------|--|------------------------------------|
| M-2 | Non-coated 62HRC | 0.77 | 4250 | 1 |
| DLC | PACVD | 0.12 | 1.79 | 2374 |
| i-C | HFCVD | 0.19 | 10 | 425 |
| TiN-1 | PVD electron gun | 0.53 | 130 | 33 |
| TiN-2 | PVD E.C.A. | 0.69 | 130 | 33 |
| TiN-3 | PVD E.C.A. low temp. | 0.67 | 70 | 61 |
| TiC-1 | CVD | 0.36 | 130 | 33 |
| TiC-2 | PVD electron gun | 0.35 | 142 | 30 |
| VC | Salt bath | 0.72 | - | - |
| Ti(C,N) | PVD electron gun | 0.46 | 70 | 61 |
| (Ti,Al) N-A | PVD E.C.A. Ti/Al=83/17 | 0.54 | 555 | 7.7 |
| (Ti,Al) N-B | PVD E.C.A. Ti/Al=75/25 | 0.68 | 824 | 5.2 |
| (Ti,Al) N-C | PVD E.C.A. Ti/Al=53/47 | 0.75 | 924 | 4.6 |
| CrN | Magnetron non-balance | 0.39 | 393 | 10.8 |
| CrxNy | Magnetron non-balance | 0.50 | 1410 | 3 |
| Cr sol-sol | Magnetron non-balance | 0.61 | 1060 | 4 |
| Cr2n | Magnetron non-balance | 0.77 | 1490 | 2.9 |

M.I.M 模具表面處理之建議

梧濟工業

結論

M.I.M粉末成型模具材料之選用必需滿足以下工藝要求:

1. 含高釩(V)6%~10%之工具鋼以對抗不銹鋼之粘著磨耗，硬度HRC:54~62
Böhler:K-390,K-490,K-890
2. 含Co,W,Mo之工具鋼對抗刮損磨耗
Böhler:S-290,S-390,S-690 硬度HRC:62~66
3. 選擇高強度之模座材料以提高模具結構強度
Böhler:W-360 Buderus:1.2344,1.2714
4. 嚴謹的熱處理工藝流程以確保工具鋼相變態之完整性，以提高尺寸穩定性與抗時效變寸。

Thank you