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DESIGN IMPROVEMENTS FOR
CYCLIC INJECTION MOLDS

PDO 6984800, Final Report

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Prepared by M. J. Bronson and D. C. Bruegge, D/835, under
PDO 6984800.

Studies were conducted of mold alloys, fabrication methods, and oil loop designs to improve the design and fabrication of cyclic injection molds. It was concluded that maraging steels are the best alloys for mold applications, but their unavailability and limited size made them impractical for most mold applications. Alloys considered acceptable, but requiring better weld quality, are the following: H13, Viscount 44, 420 stainless steel, A6, and A8. The weldability of most of the alloys was rated from poor to fair because of a high frequency of cracks. Mold temperature response of the molds studied varied between 9 to 29°F/minute (5 to 17°C/minute). This rate of temperature change is inversely proportional to the channel-to-surface thickness and decreases by approximately 20°F/minute/inch (0.42°C/minute/mm) of thickness increase. The channel-to-surface thickness range was within 1 to 3 inches (25.4 to 76.2 mm).

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SUMMARY

Thermal cycling of injection molds is a relatively new technology. Unlike conventional constant temperature molds, thermally cycled molds allow the injection of the plastic melt above the glass transition temperature and allow controlled cooling through the glass transition temperature. The molding that results is more stable, and key dimensional criteria such as flatness and contour are controllable.

The purpose of this project was the development of conceptual guidelines for design and fabrication of cyclic molds. Primary areas of interest were mold materials, welding and heat-treating fabrication processes, and relationships between oil loop design and transient temperature response of the mold design.

Phase I comprised the investigation of tooling alloys and mold fabrication processes. Small thermal cyclic test samples, fabricated from 16 alloys, were studied for hardness, machinability, surface condition, weldability, and internal discontinuities and were leak-tested for cracks in the welds.

Most of the alloys studied achieved adequate hardness, approximately R_c 50, for obtaining the desired combination of strength and toughness. Machinability and surface condition of most alloys were good, although some alloys had a tendency to corrode more readily than others. A correlation between surface stress and weld quality was not found. The residual surface stress depends primarily upon surface finish.

The weldability of most of the alloys was rated from poor to fair because of a high frequency of cracks and leakage of the test samples. More emphasis is needed in the area of welding rod selection. Some strength in the weld may have to be sacrificed to obtain ductility necessary to weld without cracking problems.

Maraging steels are considered the best alloys for mold applications, but their unavailability and limited size make them impractical for most mold applications. Alloys considered acceptable, but requiring better weld quality, are the following: H13, Viscount 44, 420 stainless steel (SS), A6, and A8.

The Phase II activity consisted of design evaluation of physical mold constants and thermal responses. Two mold mounts and ten sets of inserts were fabricated. The inserts featured three distinct channel cross sections and variations in the distance from the channel to the molding surface.

Initial thermal response experiments were designed and performed by subjecting three of the medium channel cavity inserts to constant and cyclic temperature tests. The inserts were thermally cycled to provide a measure of response to a 100°F (56°C) drop in oil temperature (from 300 to 200°F) (148 to 93°C). Mold temperature response varied between 9 to 29°F/minute (5 to 17°C/minute). This rate of temperature change is inversely proportional to the channel-to-surface thickness and decreases by approximately 20°F/minute/inch (0.42°C/minute/mm) of thickness increase. The channel-to-surface thickness range was within 1 to 3 inches (25.4 to 76.2 mm).

Future work on this endeavor, which will be conducted on process engineering account 041233-31, includes completion of oil loop design evaluation and analysis of mold alloys and fabrication methods.

DISCUSSION

SCOPE AND PURPOSE

The objective of this project was to investigate mold fabrication techniques and dimensional-thermal relationships of mold designs to provide conceptual guidelines for the design and fabrication of cyclic molds.

The purpose of investigating fabrication techniques was to determine the effects of mold materials and fabrication processes on mold quality. Welded and hardened tool steel alloys were studied for relationships to weldability, machinability, and crack resistance.

The purpose of design evaluation was to equate physical mold constants to thermal responses. Relationships between oil loop design and transient temperature response of the molding surface was sought. Oil channel-to-molding surface distance, oil channel density, and oil channel spacing were studied for effects on heating rates and thermal gradients.

PRIOR WORK

No previous work is known to have been conducted for this purpose.

ACTIVITY

Phase I. Mold Alloys and Fabrication Investigations

The objective of Phase I was to investigate hardened and welded alloys which offer potential mold fabrication capability. The following 16 alloys were fabricated into small thermal cyclic test samples, which were checked for hardness, residual surface stress, leakage, weldability, internal discontinuities, and machinability: H13, Viscount 44, 420 SS, 440C SS, AISI 1018, P20, beryllium-copper (Be-Cu), S5, A6, A8, 4130, 4140, Vascomax 200, Vascomax 250, Vascomax 300, and Vascomax 350.

Alloy Descriptions¹

The alloys are described in terms of chemical composition, physical and mechanical properties, such as strength (deformation and wear), toughness (resistance to breakage or cracking-brittleness), hardness, and dimensional stability. Recommended uses and limitations of the alloys, as they are related to injection mold fabrication, are included. Data on the chemical composition, strength, and elongation are provided in the Appendix.

In the chemical analysis, carbon (C) and, to a lesser extent, manganese (Mn) add strength and hardness to the alloys. Manganese also acts as a deoxidizer and enhances hardenability (deep hardening). But excess C or Mn makes the alloy brittle. Silicon (Si) acts as a deoxidizer, increases decarburization, and adds strength. When combined with Mn, Si also adds ductility. Nickel (Ni) increases toughness, surface hardness, and corrosion resistance. Ni lessens distortion in quenching. Chromium (Cr) enhances hardenability, adds strength, promotes decarburization, retards corrosion, and adds heat resistance. Molybdenum (Mo) promotes hardenability and toughness, enhances corrosion resistance, and adds high temperature strength. Vanadium (V) acts as a powerful deoxidizer and adds high surface hardness. Sulphur (S) and phosphorous (P) are considered undesirable because they add nothing to alloy quality. Iron (Fe) constitutes the balance of the alloy compositions except where otherwise indicated.

H13 Tool Steel. H13 is a hot work (Chromium) tool steel used primarily for large die casting dies, extrusion dies, and forging dies. It has very deep hardenability, very low distortion (air hardening), and high toughness. H13 is usually heat-treated to Rockwell hardness C-scale (R_C) 50 to 54, but may be heat-treated to any hardness in the range from R_C 28 to 54. These mechanical properties make H13 a good material for mold applications.

Viscount 44 Tool Steel. Viscount 44 is a hot work (chromium) tool steel similar to H13 with very deep hardenability, very low distortion (air hardening), and high toughness, making it a good choice for mold applications. Viscount 44 may be heat-treated from R_C 28 to 54.

420 SS. 420 SS is an acceptable material for mold applications because of its deep hardening and low distortion (if air hardened), but it has high hardness (R_C 49 to 52) and only moderate toughness. High chromium content provides the stainless properties: corrosion resistance, high strength, cleanness, uniformity, and mirror-like finishes. Alloy 420 SS is not recommended for high temperature use as mechanical properties and corrosion resistance drop when used above 800°F (427°C).

440C SS. Alloy 440C SS is not a satisfactory material for mold applications because the large carbon content gives it very high hardness (R_C 52 to 60) and moderate toughness. High chromium content provides the desirable stainless properties. 440C SS is not recommended for use above 800°F (427°C) because stainless properties are impaired.

AISI 1018 Low-Carbon Steel. The low hardness (R_b 65 to 85) and high distortion of AISI 1018 make this material unsatisfactory for mold applications.

P20 Tool Steel. P20 is mold tool steel similar to 4135 but higher in Cr and Mo. It is not considered a good material for mold applications because of its shallow depth of hardening and distortion due to oil quench. P20 may be heat-treated from R_c 24 to 50.

Be-Cu Alloy 170. Be-Cu alloy 170 can be used for mold applications, but it has rather low hardness R_c 33 to 38). Be-Cu alloy 172 would be harder (R_c 36 to 41).

S5 Tool Steel. S5 is shock resistant tool steel, which is not a good material for mold applications because of its medium depth of hardening and distortion caused by oil quench. S5 may be heat-treated from R_c 31 to 60.

A6 Tool Steel. A6 is an air hardening tool steel, which is an adequate material for mold applications because of its deep hardening, low distortion (air hardening), and medium toughness. A fairly high carbon content makes A6, at R_c 48 to 60, harder than, and not as tough as, H13.

A8 Tool Steel. A8 is an air hardening tool steel, which is also an adequate material for mold applications because of its deep hardening, low distortion, and high toughness. A8, at R_c 48 to 60, is harder than, and not as tough as, H13.

4130 Low-Alloy Steel. Alloy 4130 is not satisfactory for mold applications because of its shallow depth of hardening and high distortion caused by oil quench. It may be heat-treated from R_c 26 to 43.

4140 Low-Alloy Steel. 4140 is not a satisfactory material for mold applications because of its shallow depth of hardening and high distortion caused by oil quench. It may be heat-treated from R_c 26 to 43.

Vascomax Type 200 Maraging Steel. Vascomax Type 200 is a good material for mold applications because of its depth of hardening, low distortion, very high toughness, and high strength. It may be heat-treated from R_c 44 to 48.

Vascomax Type 250 Maraging Steel. Vascomax 250 is also a good material for mold applications because of its depth of hardening, low distortion, very high toughness, and high strength. It may be heat-treated from R_c 48 to 50.

Vascomax Type 300 Maraging Steel. Vascomax 300 is an adequate material for mold applications because of its deep hardening characteristics, high strength, and low distortions; but it is not as tough as Types 200 and 250 and is slightly harder (R_c 51 to 55).

Vascomax Type 350 Maraging Steel. Vascomax 350 is an adequate material for mold applications because of its deep hardening qualities, high strength, and low distortion; but it is not as tough as Types 200 and 250 and is somewhat harder (R_c 52 to 58).

Fabrication of Test Samples

Heat-Treat Samples. The alloys were fabricated into two types of simulated miniature mold inserts. The first design, designated 6984800-003 (Figure 1) was a block 3.5 by 3.5 inches by 1.0 inch (89 by 89 by 25.4 mm) with a 0.5-inch-diameter (13 mm) right-angle oil channel inside the block. Some alloys were supplied in round stock, and the corresponding samples were disks 4.0 inches (10.2 mm) in diameter and 1 inch (25.4 mm) thick. As part of the tool design, seven variations (including heat-treat variables and post-hardening variables) of each alloy were fabricated. The experimental fabrication matrix for each steel alloy is given in Table 1.

The heat-treat variations included a base or recommended cycle to produce a balance of toughness and hardness. The austenizing temperatures were varied to produce the ± 1 heat-treat levels. Data for the heat-treat variable selection are listed in Table 2.

Weld Samples. The second insert designated 6984800-004 (Figure 2) was also a block or disk of similar dimensions, but it was a welded configuration. The experimental fabrication matrix for the weld samples is given in Table 3.

The base weld cycles consisted of the Tungsten Inert Gas (TIG) hand-welding method, using argon as the inert shield gas. A Lincoln Ideal Arc Welder was used for the TIG hand welding. Bare welding rods were selected with compositions matching as closely as possible those of the alloys. If suggested for the particular alloy, Variation 1 in the weld cycle consisted of manual arc welding, using a Hobart welder. Coated welding rods were selected to match the alloy composition. Variation 1 consisted of TIG hand-welding for some alloys, using a bare welding rod of slightly different composition. Variation 2 consisted of either TIG or hand arc-welding, using a third type of welding rod. If no compatible rod was available for either variation in the weld cycle, the base weld cycle was repeated. The weld cycle selections for the alloys are listed in Table 4. The composition of the welding rods is listed in Table 5.

Manual arc welding spatters less than TIG welding, producing a weld with fewer pin holes and less porosity; but manual arc is a slower process requiring short passes and peening to remove slag.

Text continued on page 19. 1

Figure 1. Heat-Treat Sample

Table 1. Experimental Fabrication Matrix for Steel Alloy Samples

Alloy Sample	Heat-Treat Cycle	Post-Hardening Machining
1	0 (Base Cycle)	0 (None)
2	0	0
3	0	0
4	+1 (Low Austenize)	+1 (Grind all faces)
5	+1	-1 (EDM cavity)
6	-1 (High Austenize)	-1
7	-1	+1

Table 2. Heat-Treat Processes

Material	Preheat (°F) (°C)	Austenize (°F) (°C)			Time (Minutes)	Stress Relief (30 Minutes) (°F) (°C)	Quench
		Base	Low	High			
H13	1500 (816)	1860 (1016)	1775 (968)	1950 (1066)	20	300 (149)	Air
Viscount 44	1500 (816)	1860 (1016)	1775 (968)	1950 (1066)	20		Air
420 SS	1300 (704)	1850 (1010)	1750 (954)	1950 (1066)	90		Oil, followed by 2 hr at -120°F (-84°C)
440C SS	1300 (704)	1900 (1038)	1800 (982)	2000 (1093)	90		Oil, followed by -120°F (-84°C) for 2 hr continuous cooling from austenizing temperature to cold transformation temper- ature
AISI 1018	None	1550 (843)	1450 (788)	1650 (899)	15 at mold temp		
P20							
Be-Cu 170	1400 (760)	1650 (899)	1550 (843)	1750 (954)	15 at mold temp		
S5							
A6	1200 (649)	1560 (849)	1475 (802)	1650 (899)	35		Air
A8	1450 (788)	1825 (996)	1750 (954)	1900 (1038)	30		Air
4130	None	1550 (843)	1450 (788)	1650 (899)	90	Oil	
4140	None	1560 (849)	1475 (802)	1650 (899)	90	Oil	
Vascomax 200	*					Air	
Vascomax 250	*					Air	
Vascomax 300	*					Air	
Vascomax 350	*					Air	

*Solution-treat at 1500°F (816°C) for 30 minutes (if not previously done by vendor).

Table 2 Continued. Heat-Treat Processes

Temper (2 Hours) (°F) (°C)	Carburize (9 Hours) (°F) (°C)			Age (3 Hours) (°F) (°C)		
	Base	Low	High	Base	Low	High
1000 (538)						
1000 (538)						
1075 (579)						
275 (135)						
	1625 (885)	1400 (760)	1850 (1010)			
800 (427)				610 (321)	475 (246)	700 (371)
400 (204)						
350 (177)						
1000 (538)						
850 (454)						
850 (454)						
				900 (482)	850 (454)	--
				900 (482)	850 (454)	950 (510)
				900 (482)	850 (454)	950 (510)
				950 (510)	900 (482)	1000 (538)

Figure 2. Welded Sample

Table 3. Experimental Fabrication Matrix for Weld Samples

Alloy Samples	Weld Cycle	Post-Hardening Machining
1	0 (Base)	0 (None)
2	0	-1 (EDM Cavity)
3	0	+1 (Grind all faces)
4	+1 (Variation 1)	-1
5	+1	+1
6	-1 (Variation 2)	+1
7	-1	-1

H13, Viscount 44, 420, 440C, P20, S5, A8, 4130 and 4140 require annealing prior to welding to relieve machining stresses. They also require extensive heat treat for hardening after welding. AISI 1018 does not require annealing, but carburizing is required to obtain alloy hardness. Vascomax Types 200, 250, 300, and 350, and Be-Cu have very simple heat-treat requirements. The alloys must be solution annealed, but this is generally done by the vendor. Hardness is obtained by a simple aging process.

H13, Viscount 44, A6, and A8 also require very high preheat (1000°F) (537°C) prior to welding. Alloys 420, 440C, P20, Be-Cu, S5, 4130, and 4140 require a somewhat lower preheat (500°F) (260°C). AISI 1018 and the Vascomax series of alloys require no preheat prior to welding. When details of substantial size are being welded, high preheat requirements make the process difficult and discomforting for the welder.

Inspection of Test Samples

The steel alloy samples were inspected for hardness, internal discontinuities, leakage, surface condition, and residual surface stress.

Alloy Hardness. Rockwell hardness readings were taken in the center of one face on the samples (Table 6). Hardness of the weld is also indicated if it is significantly different from the parent metal.

The austenizing temperature appeared to have no effect on hardness for the heat-treat alloys H13, Viscount 44, 420 SS, 440C SS, P20, S5, A8, 4130, and 4140. The aging temperature had no effect on hardness for Be-Cu, Vascomax 200, and Vascomax 250. A lower

Table 4. Welding Processes

Material	Weld Cycle	Weld Preheat and Postheat (°F) (°C)	Weld Method	Electrode Designation	Electrode Size (in.) (mm)	Passes (avg)
H13	Base	800 to 1100 (427 to 593)	Hand TIG	Eureka 1000A, Bare	0.094 (2.38)	3
	Var. 1	800 to 1100 (427 to 593)	Hand Arc	Eureka 31, Coated	0.125 (3.18)	3
	Var. 2	800 to 1100 (427 to 593)	Hand TIG	Eureka 31A, Bare	0.063 (1.59)	3
Viscount 44	Base	800 to 1100 (427 to 593)	Hand TIG	Eureka 72A, Bare	0.094 (2.38)	3
	Var. 1	800 to 1100 (427 to 593)	Hand Arc	Eureka 72, Coated	0.125 (3.18)	3
	Var. 2	800 to 1100 (427 to 593)	Hand TIG	Eureka 1000A, Bare	0.094 (2.38)	3
420 SS	Base	400 to 600 (204 to 316)	Hand TIG	420 SS, Bare	0.094 (2.38)	4
	Var. 1	400 to 600 (204 to 316)	Hand TIG	308 SS, Bare	0.094 (2.38)	4
440C SS	Base	400 to 600 (204 to 316)	Hand TIG	420 SS, Bare	0.094 (2.38)	4
	Var. 1	400 to 600 (204 to 316)	Hand TIG	308 SS, Bare	0.094 (2.38)	4
AISI 1018	Base	None	Hand TIG	Mild Steel No. 2, Bare	0.125 (3.18)	3
	Var. 1	None	Hand Arc	Lincoln 47, Coated	0.125 (3.18)	3
	Var. 2	None	Hand Arc	Lincoln 7, Coated	0.188 (4.77)	3
P20	Base	400 (204)	Hand TIG	P20, Bare	0.094 (2.38)	12
	Var. 1	400 (204)	Hand Arc	Eureka 130A, Coated	0.125 (3.18)	12
	Var. 2	400 (204)	Hand TIG	Eureka 130A, Bare	0.094 (2.38)	12
Be-Cu	Base	300 to 400 (149 to 204)	Hand TIG	Ampco 160, Bare	0.063 (1.59)	5
	Var. 1	300 to 400 (149 to 204)	Hand TIG	Ampco 250, Bare	0.125 (3.18)	4
	Var. 2	300 to 400 (149 to 204)	Hand TIG	Ampco 300, Bare	0.125 (3.18)	4

Table 4 Continued. Welding Processes

Material	Weld Cycle	Weld Preheat and Postheat (°F) (°C)	Weld Method	Electrode Designation	Electrode Size (in.) (mm)	Passes (avg)
S5	Base	400 (204)	Hand TIG	Bare Rod for S5 and S7	0.125 (3.18)	4
	Var. 1	400 (204)	Hand Arc	Eureka 72, Coated	0.125 (3.18)	4
	Var. 2	400 (204)	Hand TIG	Eureka 72A, Bare	0.094 (2.38)	4
A6	Base	800 to 1100 (427 to 593)	Hand TIG	Air 40A, Bare	0.063 (1.59)	5
	Var. 1	800 to 1100 (427 to 593)	Hand Arc	Air 40, Coated	0.125 (3.18)	3
A8	Base	800 to 1100 (427 to 593)	Hand TIG	Eureka 1215A, Bare	0.094 (2.38)	5
	Var. 1	800 to 1100 (427 to 593)	Hand Arc	Eureka 1215, Coated	0.094 (2.38)	3
	Var. 2	800 to 1100 (427 to 593)	Hand TIG	Eureka 1220A, Bare	0.094 (2.38)	5
4130	Base	350 to 500 (177 to 260)	Hand TIG	Eureka 130A, Bare	0.094 (2.38)	6
	Var. 1	350 to 500 (177 to 260)	Hand Arc	Eureka 130, Coated	0.125 (3.18)	6
	Var. 2	350 to 500 (177 to 260)	Hand TIG	Eureka P20, Bare	0.094 (2.38)	6
4140	Base	350 to 500 (177 to 260)	Hand TIG	Eureka 130A, Bare	0.094 (2.38)	6
	Var. 1	350 to 500 (177 to 260)	Hand Arc	Eureka 130, Coated	0.125 (3.18)	6
	Var. 2	350 to 500 (177 to 260)	Hand TIG	Eureka P20, Bare	0.094 (2.38)	5
Vascomax 200	Base	None	Hand TIG	Marweld 250W, Bare	0.094 (2.38)	5
Vascomax 250	Base	None	Hand TIG	Marweld 250W, Bare	0.094 (2.38)	5
Vascomax 300	Base	None	Hand TIG	Marweld 300, Bare	0.063 (1.59)	5
Vascomax 350	Base	None	Hand TIG	Marweld 300, Bare	0.063 (1.59)	5

Table 5. Chemical Composition of Welding Rods

Welding Rod	Chemical Composition (Percent)						
	C	Si	Mn	Cr	Ni	Mo	W
Lincoln 7 Electrode						0.50	
Lincoln 47 Electrode						0.50	
Air 40A, Bare	0.70	0.30	2.00	1.00		1.35	
Eureka 72A, Bare	0.36	0.84	0.28	5.00		1.39	1.36
Eureka 130A, Bare	0.29	0.29	0.57	0.96		0.17	
Eureka 1215A, Bare	1.02	0.28	0.65	5.50		1.15	
Eureka 1220A, Bare	2.15	0.32	0.25	11.75		0.70	
Eureka 31A, Bare	0.37	1.00	0.35	5.25		1.25	
Eureka 1000A, Bare	0.37 to 0.43	0.80 to 1.00	0.20 to 0.40	4.75 to 4.25		1.20 to 1.40	
Marweld 300, Bare	0.03 max	0.10 max	0.10 max		18.50	4.80	
Marweld 250W, Bare	0.03 max	0.10 max	0.10 max		18.00 to 19.00	4.60 to 5.00	
Air 40 Electrode	0.70 to 0.75		1.00 to 1.25	0.70 to 0.75	1.65 to 1.75	1.60 to 1.70	
Eureka 72 Electrode	0.25 to 0.35		0.30 to 0.40	4.75 to 5.25		2.00 to 2.50	2.50 to 3.00
Eureka 130 Electrode	0.25 to 0.35		0.50 to 0.80	1.00 to 1.25		0.35 to 0.50	
Eureka 1215 Elec- trode	0.75 to 1.00		0.40 to 0.60	4.50 to 5.00		1.75 to 2.00	1.00 to 1.10
Eurekamold P20, Bare	0.30	0.50	0.80	1.65		0.40	
Ampco 160, Bare							
Ampco 250, Bare							
Ampco 300, Bare							
Stainless 308, Bare	0.06	0.40	1.80	20.0	9.70		
Stainless 420, Bare	over 0.15	1.00 max	1.00 max	12.00 to 14.00			
502	0.05 max	0.50 to 0.90	0.60 to 0.85	0.40 to 0.60		0.45 to 0.65	

Table 5 Continued. Chemical Composition of Welding Rods

Chemical Composition (Percent)									
V	Co	Ti	Fe	Cu	S	P	Al	Other	Comments
0.44			Balance						Similar to A6
			Balance						
			Balance						
			Balance						
			Balance						
			Balance						
			Balance						
			Balance						
			Balance						
			Balance						
0.30	9.00	0.60	Balance		0.03 max	0.03 max	0.10	Similar to H11	
0.42			Balance		0.01 max	0.01 max			
1.05			Balance		0.03 max	0.03 max			
0.40 to 0.60			Balance						
			Balance						
			Balance						
			Balance						
			Balance						
			Balance						
			Balance						
0.30 to 0.40	7.00 to 8.50	0.30 to 0.50	Balance						Similar to A6
			Balance						Similar to H12
			Balance						Similar to 4130
			Balance						
			Balance						
			Balance						
			Balance						
			Balance						
			Balance						
			Balance						
0.45 to 0.55			4.17	85.35			9.57	0.81	Similar to 4135
			5.32	81.75			12.08	0.95	
			5.39	80.87			12.64	1.10	
			Balance						
			Balance						
			Balance						
			Balance						
			Balance						
			Balance						
			Balance						
			0.01	0.02					
			0.03 max	0.04 max					
			Balance		0.03 max	0.03 max			

Table 6. Hardness of Test Blocks From Designs 6984800-003 and -004

Material	Design	Rock- well Scale	Sample Number						
			1	2	3	4	5	6	7
H13	-003	C	51	57	55	42	47	51	43
	-004	C	56	53	57	56	57	58	57
Viscount 44	-003	C	43	44	43	43	44	42	43
	-004	C	55	53	52	52	54	53	53
420 SS	-003	C	33	28	33	31	33	35	31
	-004	C	32	37	46	34 (10)	45 (10)	44	39
440C SS	-003	C	57	59	60	55	57	64	62
	-004	C	58	57	57	56 (20)	60 (20)	60	58
AISI 1018	-003	B	97	98	96	75	73	95	99
	-004	B	78	77	78	78	77	76	77
P20	-003	C	41	45	45	45	46	45	45
	-004	C	56	45	45	43	45	45	45
Beryllium- Copper	-003	C	32	33	31	31	30	33	32
	-004	C	79 (3)	27 (9)	30 (4)	34	18	24	30
S5	-003	C	54	52	50	48	59	50	57
	-004	C	48 (56)	50 (56)	48 (58)	49 (52)	48 (53)	47 (53)	46 (50)
A6	-003	C1	57	60	57	41	41	54	56
	-004	C	58	54	53	57	56	57	58
A8	-003	C	48	54	58	52	45	61	52
	-004	C	55	53	54	53	53	57	55
4130	-003	C	29	29	29	25	28	36	22
	-004	C	42	40	31	35	40	36	34
4140	-003	C	38	47	37	42	44	48	33
	-004	C	45	44	47	45	46	46	44
Vascomax 200	-003	C	37	42	40	34	38	44	43
	-004	C	43 (51)	42 (48)	41 (46)	43 (51)	41 (50)	43	43 (48)
Vascomax 250	-003	C	40	36	39	36	36	39	49
	-004	C	49 (53)	47 (52)	44 (51)	48 (52)	44 (49)	48 (52)	48 (50)
Vascomax 300	-003	C	39	39	37	34	33	50	51
	-004	C	52	46	46	49	48	48	51
Vascomax 350	-003	C	56	57	57	38	40	40	38
	-004	C	54	55	42	51	47	51	55
Note: Numbers in parentheses indicate hardness of the weld if substantially different from that of the parent metal.									

austenizing temperature made A6 significantly softer. A lower aging temperature made Vascomax 300 slightly softer, and a higher aging temperature made it significantly harder. Both the higher and lower aging temperatures made Vascomax 350 significantly softer. A lower carburizing temperature made AISI 1018 significantly softer.

In mold applications a hardness of approximately R_C 50 is usually desired to obtain a good combination of strength and toughness. AISI 1018 and Be-Cu alloy 170 cannot attain this high hardness. Alloys 440C, A6, and A8 have very high hardness that reduces toughness. While lower hardness can be obtained, it cannot be done without impairing other important properties such as corrosion resistance and strength. A good combination of hardness and toughness can be obtained with H13, Viscount 44, 420 SS, and Vascomax Types 200, 250, 300, and 350, if the optimal heat-treat procedure is known.

In-depth hardening is also desirable in mold applications. Alloys P20, 4130, and 4140 provide only shallow hardening, while S5 provides medium depth hardening. The remaining alloys have deep-hardening qualities.

In welded details, the hardness of the weld should be similar to that of the parent metal which is determined by proper welding rod selection. The second welding process used on 420 and 440C, in which a 308 stainless steel was employed, is undesirable because the hardness of the welds were R_C 10 to 20 while the hardness of the 420 parent metal was R_C 34 to 45 and that of 440C was approximately R_C 60. When welding Process 1 was used with Be-Cu, employing bare rod Ampco 160, a weld much softer than the parent metal was produced; weld hardness was R_b 3 to 9, and Be-Cu parent metal was R_b 19 to 30. Welding rod bare Marweld 250W, used on Vascomax 200 and 250, produced welds slightly harder than the parent metal; the weld was R_C 46 to 53, Vascomax 200 was R_C 41 to 43, and Vascomax 250 was R_C 44 to 49. The three weld processes produced welds slightly harder than the parent metal when S5 was used.

Alloy Discontinuities. Magnetic particle (dye penetrant) tests were performed on all samples to indicate surface cracks. X-ray photographs were also taken, which proved to be more valuable because the sizes, shapes, and types of internal discontinuities could be detected. No indications of discontinuities were noticed on the heat-treat alloys. The internal discontinuities of the weld samples, also indicated on x-rays, are categorized by the size and types of flow-gas porosity, incomplete fusion, slag or tungsten inclusion, longitudinal or transverse weld cracks, base metal cracks, melt-through, and icicles (Table 7).

[illegible]

Table 7 Continued. Internal Discontinuities and Leakage

Material and Serial Number	Gas Porosity	Incomplete Fusion	Inclusions		Weld Cracks		Cracks Base Metal	Melt-Through and Icicles	Leakage
			Slag	Tungsten	Longitudinal	Transverse			
420 SS									
1	2				1				
2	2		1		1			1	Yes
3	2		1		1			1	No
4	1	2						1	No
5	1				2	4	4	1	Yes
6	2	1	1		2			1	Yes
7	2	1	1		4			1	Yes
440C SS									
1	1						4	1	Yes
2	1				1		4	1	Yes
3	1				4		4	1	Yes
4	1				2		4	1	Yes
5	1					1	4	1	Yes
6	1						4	1	Yes
7	2						4	1	Yes
Discontinuity 1 - Small 2 - Medium 3 - Large 4 - Gross									

Table 7 Continued. Internal Discontinuities and Leakage

Material and Serial Number	Gas Porosity	Incomplete Fusion	Inclusions		Weld Cracks		Cracks Base Metal	Melt-Through and Icicles	Leakage
			Slag	Tungsten	Longitudinal	Transverse			
S5									
1					3	1	4		Yes
2	1				4				No
3	2				2			2	Yes
4	1	3			1			3	Yes
5	2				4	1		1	Yes
6	3				2				Yes
7	2	3			2		4	1	Yes
A6									
1	3	2			2				Yes
2	2				1			1	Yes
3	2				1				No
4	1		2		1			1	No
5	1	2			1			1	No
6	3				1				Yes
7	2				2			1	No
A8									
1	2				3			2	Yes
2	2			2	3			1	Yes
3	1				4			2	Yes
4	1				4			1	Yes
5	1	2			4			1	Yes
6	1	4			4			1	Yes
7	1				4			1	Yes
Discontinuity 1 - Small 2 - Medium 3 - Large 4 - Gross									

[illegible]

Table 7 Continued. Internal Discontinuities and Leakage

Material and Serial Number	Gas Porosity	Incomplete Fusion	Inclusions		Weld Cracks		Cracks Base Metal	Melt-Through and Icicles	Leakage
			Slag	Tungsten	Longitudinal	Transverse			
Vascomax 250									
1	1				2				No
2	1				2			1	No
3	1			2	1			1	No
4	1		2	2	1				No
5	1		2		1			1	No
6	1			2	1				No
7	1		2						No
Vascomax 300									
1	1			2					No
2	1				1				No
3				2	1				No
4	1				2			1	No
5	1	2		2	1				No
6	1			2	1				No
7	1	2	2	2	2				No
Vascomax 350									
1	1			2	2	1		1	No
2	2				2	1		1	No
3	2		2		2			1	No
4	2		2		2			1	No
5	1				2	1			No
6	1				1			1	No
7	2				2				Yes
Discontinuity 1 - Small 2 - Medium 3 - Large 4 - Gross									

Leak tests were performed on the samples, using the right-angle channels. None of the heat-treat samples leaked. The weld samples which leaked are indicated in Table 7.

H-13. All three samples leaked that were welded with the base process TIG, using a bare Eureka 1000A rod, and x-rays indicated porosity in the welds. Both samples leaked that were welded with process Variation 1, hand arc, using a coated Eureka 31A rod, and x-rays indicated porosity and cracks in the welds. The cracks and some pits were visible on the sample surfaces. One of two samples leaked from weld process Variation 2, TIG, using a bare Eureka 31A rod. X-rays indicated porosity and melt-through into the oil channel.

Viscount 44 Tool Steel. When weld process Variation 1, hand arc, was used, with a coated Eureka 72 Rod, the two Viscount 44 samples did not leak; but x-rays showed incomplete fusion and cracks in these welds. The base weld cycle TIG, using a bare Eureka 72A rod, had indications of large amounts of melt-through into the oil channel. Only one of the three samples using the base weld cycle did not leak. With weld cycle Variation 2, TIG, using a bare Eureka 1000A rod, both samples leaked. Both of these samples had cracks visible on the surface.

420 SS. Two of the five 420 SS samples, welded with the base weld cycle TIG, using a 420 SS rod, did not leak; but x-rays indicated porosity in all welds and cracks in some of the leaking samples. Pits caused by the porosity were also visible on the sample surface. One of the two samples from weld Variation 1, TIG, using a bare 308 SS rod, did not leak. The other sample did leak, and x-rays indicated very large cracks in the sample which were also visible on the surface of the sample.

440C SS. One of the five 440C SS samples welded with a bare 420 SS rod, showed leaks, and both samples leaked that were welded with a 308 SS rod. X-ray indicated very large cracks in all of the 440C samples. The long cracks were visible on the surface of most samples.

AISI 1018 Low-Carbon Steel. All AISI 1018 samples leaked. X-rays from samples welded with base weld cycle TIG, using a bare No. 2 mild steel rod, indicated large cracks with some porosity and inclusions. The welds were also very pitted on the surface.

Samples from weld Variation 1, hand arc, using a coated Lincoln No. 47 rod, had excessive areas of incomplete fusion. Samples from weld Variation 2, hand arc, using a coated Lincoln No. 7 rod, had a lesser amount of incomplete fusion. Slag pits were visible on the surface of samples from weld Variation 1.

P20 Tool Steel. The three samples from base weld cycle TIG, using a bare P20 rod, leaked. X-rays indicated much porosity and large cracks, both of which were visible on the sample surfaces. One of the two samples welded with Variation 1, hand arc, using a coated Eureka 103 rod, did not leak; but x-rays indicated long cracks in both samples which were also visible on the surface. Both samples from weld Variation 2, TIG, using a bare Eureka 130A, leaked; and x-rays again indicated large cracks which were visible on the surface.

Be-Cu Alloy 170. Two of the three samples from base weld cycle TIG, using a bare Ampco 160 rod, leaked. X-rays indicated some incomplete fusion, cracks, and large amounts of melt-through into the oil channel. All samples leaked which were welded with Variation 1, using a bare Ampco 250 rod, and with Variation 2, using a bare Ampco 300 rod. X-rays again indicated incomplete fusion and large amounts of melt-through.

S5 Tool Steel. Two of the three samples leaked which were welded with base cycle TIG, using a bare rod for S5. X-rays indicated large cracks that were visible on the surface of the samples which leaked. The remaining samples leaked which were welded with Variation 1, hand arc, using a coated Eureka 72 rod, and with Variation 2, TIG, bare Eureka 72A rod. X-rays indicated porosity and cracks in these samples.

A6 Tool Steel. Three of the five samples leaked from base weld cycle TIG, using a bare air 40A rod. X-rays indicated porosity in all the samples, and weld pits could be seen on the surface of some samples. The two samples which were welded with Variation 1, hand arc, using a coated air 40 rod, did not leak. Pits were seen on the surface of these samples, and x-ray indicated slag inclusions in one sample and incomplete fusion in the other.

A8 Tool Steel. All of the A8 samples leaked, and x-rays showed that they contained large cracks. The surface of all samples also had cracks or pits. The base weld cycle consisted of TIG welding, using a bare Eureka 1215A rod; Variation 1 consisted of hand arc welding, using a coated Eureka 1215 rod, and Variation 2 consisted of TIG welding, using a bare Eureka 1220A rod.

4130 Low-Alloy Steel. Two of the three samples leaked which were welded with the base cycle TIG, using a bare Eureka 130A rod. X-rays indicated porosity, cracks, and melt-through in the two leaking samples, and the welds were pitted on the surface. X-rays indicated tungsten inclusions in the base weld cycle samples. The two samples which were welded with Variation 1, TIG, using a bare Eureka 130A rod, did not leak. X-rays indicated incomplete fusion with this weld process. One of the two samples which were

welded with variation 2, TIG, using a bare Eureka P20 rod, showed leaks. X-rays indicated tungsten inclusion in both samples and porosity and melt-through in the leaking sample.

4140 Low-Alloy Steel. None of the samples leaked which were welded with base weld cycle TIG, using a bare Eureka 103A rod or with weld Variation 1, hand arc, using a coated Eureka 103 rod. But x-rays indicated samples from the base weld cycle had cracks, inclusions, porosity, and melt-through. Pits were also noted on the sample surfaces. Samples from weld Variation 1 had indications of cracks and incomplete fusion. One of the two samples which were welded with variation 2, TIG, using a bare Eureka P20 rod, showed leaks. X-rays indicated cracks and tungsten inclusions.

Vascomax Type 200 Maraging Steel. One of the seven samples leaked which had been welded with base weld cycle TIG, using a bare Marweld 250W rod. X-rays indicated only very small cracks and pores, but nothing could be seen on the surface.

Vascomax Type 250 Maraging Steel. None of the seven samples leaked which were welded with base weld cycle TIG, using a bare Marweld 250W rod. X-rays indicated some inclusions, small cracks, and pores, but nothing could be seen on the surface.

Vascomax Type 300 Maraging Steel. None of the seven samples leaked which had been welded with base weld cycle TIG, using a bare Marweld 300 rod. X-rays indicated some inclusions, small cracks, and pores, but nothing was detected on the surface.

Vascomax Type 350 Maraging Steel. One of the seven samples which were welded with base weld cycle TIG, using a bare Marweld 300 rod, showed leaks. X-rays indicated cracks, pores, and minor melt-through, but nothing was seen on the surface.

Machinability and Surface Condition. The alloy samples were visually inspected for condition of the ground and unground surfaces, quality of the EDM cavities, and for their ability to resist corrosion.

H13 could be ground to a good surface finish and could form a good EDM cavity, but the EDM surfaces tended to corrode. The ground and unground surfaces had slight tendencies to corrode.

Viscount 44 could also be ground to a good surface finish and could form a good EDM cavity, but the surfaces had slightly less tendency to corrode.

420 SS could be ground to a high quality surface finish and could form a good EDM cavity. Again, the surfaces were very clean and showed no sign of corrosion.

440C SS could also be ground to a high quality surface finish and could form a good EDM cavity. Again, the surfaces were very clean and showed no sign of corrosion.

AISI 1018 could be ground to a smooth surface finish and could form a good EDM cavity, but the ground and unground surfaces tended to corrode.

P20 could be ground to a smooth surface finish and could form a good EDM cavity. The ground and unground surfaces had slight tendencies to corrode.

Be-Cu could form a mirror machined surface finish, a smooth high quality ground surface, and a good EDM cavity; but the EDM surfaces had tendency to corrode.

S-5 could be ground to a good smooth surface finish and could form a good EDM cavity. The ground and unground surfaces showed slight tendencies to corrode.

A6 could be ground to a smooth surface finish and could form a good EDM cavity, but the ground and unground surfaces tended to corrode.

A-8 could be ground to a good, smooth surface finish and could form a good EDM cavity. The surfaces showed no sign of corrosion.

4130 could be ground to a smooth surface finish and could form a good EDM cavity; but the unground, ground, and EDM surfaces tended to corrode excessively.

4140 could be ground to a smooth surface finish and could form a good EDM cavity; but, again, all the surfaces had tendencies to corrode.

Vascomax 200 and Vascomax 250 could form mirror machined surface finishes, smooth high quality ground surfaces, and good EDM cavities. The surfaces also showed no signs of corrosion.

Vascomax 300 could form a good machined surface finish, a smooth high quality ground surface, and a good EDM cavity. The EDM surfaces tended to corrode, while the ground and unground surfaces showed no signs of corrosion.

Vascomax 350 could form a good machined surface finish, a smooth high quality ground surface, and a good EDM cavity. The surfaces showed no signs of corrosion.

Residual Surface Stress. These stress determinations were made by use of the x-ray diffractometer technique,² which employs x-ray to measure the lattice spacing in the stressed condition. This measurement and the basic lattice spacing in the unstressed condition can be used to determine the surface stress at the test point. Surface stress determinations were made at two points on the heat-treat samples (Figure 3) and at five points on the welded samples (Figure 4). Determinations were made in two directions at each point with a plus (+) indicating tension and a minus (-) indicating compression. A zero reading indicates an unstressed condition. Table 8 lists the surface stress results for the heat-treat samples, and Table 9 lists the results for the welded samples. Results are in pounds per square inch. It was found that for the heat-treat samples, Position 2 over the inlet portion of the oil channel tended to indicate greater surface stresses than did Position 1 in the center of the top face.

In testing the welded samples, Position 3 on the parent metal outside the weld tended to indicate lower surface stresses than did Positions 1, 2, and 4 which were in the center of the top face and in two different locations on the welds. Position 5 over the inlet portion of the oil channel again tended to indicate surface stress slightly greater than the other positions. The base heat-treat-cycle specimen for heat-treat samples A6, A8, H13, P20, AISI 1018, 4130, 4140, 420 SS, and 440C SS had lower surface stresses than did the +1 and -1 level heat-treat cycles. The +1 level heat-treat cycle for Viscount 44, Vascomax 200, and Vascomax 250 showed lowest overall surface stress. However, the lowest surface stress occurred at the -1 level for Vascomax 300 and Vascomax 350.

Residual surface stresses tended to be greater for the ground surfaces (samples 4 and 7 of the heat-treat blocks) than for the non-ground surface (sample 1), except for alloys 4130 and 4140 and the Vascomax series. In these alloys the surface finish had no effect upon the surface stress results.

Low and high austenizing temperatures appeared to have no effect upon residual surface stress, nor were correlations seen relating weld quality to surface stress. Residual stress results depend primarily upon surface finish and geometric location of the test point.

Phase II. Mold Physical-Thermal Evaluation

Phase II work consisted primarily of an oil loop design evaluation. Two mold mounts and ten sets of inserts were fabricated. The inserts featured three distinct channel cross sections and variations in the distance of the channel to the molding surface.

Initial thermal response experiments were designed and performed, using three of the ten cavity inserts. The experiments were

intended to evaluate the response to an oil temperature change and the gradient that exists across the face of the insert prior to and after the oil temperature change has been applied. Nine thermocouples across the face of each cavity insert, at a depth of approximately 0.250 inch (6.4 mm), were used to monitor insert response.

Three cavity inserts of the medium channel insert set were subjected to constant and cyclic temperature tests. Each of the nine thermocouples was recorded as the mold was dry cycled to provide a measure of response to a 100°F (37°C) drop in oil temperature (from 300 to 200°F) (148 to 93°C). Figure 5 shows graphically the temperature response of the inserts for the 100°F oil temperature change. The key points of the cycle are the mold temperatures at melt injection (T_1) and part ejection (T_2).

Figure 3. Positions of Surface Stress Determination on Heat-Treat Samples

Figure 4. Positions of Surface Stress Determination on Welded Samples

Table 8. Residual Surface Stress on Heat-Treat Blocks

Material	Block	Residual Surface Stress (kpsi) (MPa)			
		Position 1		Position 2	
		X	Y	X	Y
H13	1	-12 (-83)	-32 (-221)	-18 (-124)	-26 (-179)
	4	-98 (-676)	-32 (-221)	-110 (-758)	-40 (-276)
	7	+12 (+83)	-68 (-469)	-32 (-221)	-50 (-345)
Viscount 44	1	-40 (-276)	-72 (-496)	-44 (-303)	-170 (-1172)
	4	-80 (-552)	-36 (-248)	-78 (-538)	-38 (-262)
	7	-56 (-386)	-92 (-634)	-62 (-427)	-100 (-689)
420 SS	1	-36 (-248)	-40 (-276)		
	4	-60 (-414)	-20 (-138)		
	7	-50 (-345)	-75 (-517)		
440C SS	1	+10 (+70)	-10 (-70)		
	4	-80 (-552)	-70 (-483)		
	7	-78 (-538)	-46 (-317)		
AISI 1018	1	-50 (-345)	-48 (-331)	-34 (-234)	-46 (-317)
	4	-66 (-455)	-18 (-124)	-60 (-414)	-15 (-103)
	7	-58 (-400)	-60 (-414)	-82 (-565)	-58 (-400)
P20	1	-44 (-303)	-38 (-262)	-42 (-290)	-42 (-290)
	4	-62 (-427)	-78 (-538)	-72 (-496)	-76 (-524)
	7	-70 (-483)	-96 (-662)	-60 (-414)	-88 (-607)
S5	1	0	-10 (-69)	-60 (-414)	-50 (-345)
	4	-98 (-676)	-35 (-241)	-88 (-607)	-46 (-317)
	7	-22 (-152)	-70 (-483)	-12 (-83)	-58 (-400)
A6	1	-5 (-34)	-16 (-110)	-20 (-138)	-44 (-303)
	4	-54 (-372)	-75 (-517)	-56 (-386)	-8 (-55)
	7	-64 (-441)	-42 (-290)	-80 (-552)	-78 (-538)
A8	1	-2 (-14)	-16 (-110)	-8 (-55)	-22 (-152)
	4	-40 (-276)	-95 (-655)	-34 (-234)	-102 (-703)
	7	-90 (-621)	-52 (-359)	-88 (-607)	-64 (-441)
4130	1	-36 (-248)	-38 (-262)	-41 (-283)	-40 (-276)
	4	-74 (-510)	-22 (-152)	-83 (-572)	-22 (-152)
	7	-82 (-565)	-44 (-303)	-84 (-579)	-38 (-262)
4140	1	-32 (-221)	-45 (-310)	-40 (-276)	-36 (-248)
	4	-92 (-634)	-40 (-276)	-72 (-496)	-34 (-234)
	7	-68 (-469)	-16 (-110)	-58 (-400)	-10 (-70)
Vascomax 200	1	-76 (-524)	-88 (-607)	-140 (-965)	-80 (-552)
	4	-55 (-379)	-86 (-593)	-48 (-331)	-86 (-593)
	7	-85 (-586)	-64 (-441)	-86 (-593)	-64 (-441)
Vascomax 250	1	-66 (-455)	-114 (-786)	-108 (-745)	-72 (-496)
	4	-82 (-565)	-94 (-648)	-56 (-386)	-84 (-579)
	7	-80 (-552)	-94 (-648)	-84 (-579)	-106 (-731)
Vascomax 300	1	-110 (-758)	-84 (-579)	-98 (-676)	-92 (-634)
	4	-70 (-483)	-100 (-689)	-50 (-345)	-78 (-538)
	7	-67 (-462)	-42 (-290)	-66 (-455)	-48 (-331)
Vascomax 350	1	-58 (-400)	-62 (-427)	-64 (-441)	-64 (-441)
	4	-74 (-510)	-50 (-345)	-84 (-579)	-55 (-379)
	7	-70 (-483)	-54 (-372)	-70 (-483)	-48 (-331)

Table 9. Residual Surface Stress on Welded Blocks

Material	Block Number	Residual Surface Stress (kpsi) (MPa)			
		Position 1		Position 2	
		X	Y	X	Y
H13	1	-4 (-28)	-12 (-83)	-8 (-55)	-7 (-48)
	4	-8 (-55)	-22 (-152)	-8 (-55)	-10 (-69)
	7	-10 (-69)	0	-10 (-69)	-12 (-83)
Viscount 44	1	-6 (-41)	-26 (-179)	-24 (-165)	-20 (-138)
	4	-14 (-97)	+5 (+34)	-7 (-48)	-6 (-41)
	7	+4 (+28)	0	0	-10 (-69)
420 SS	1	-26 (-179)	-24 (-165)	-12 (-83)	-54 (-372)
	4	-40 (-276)	-38 (-262)	-14 (-97)	-40 (-276)
	7	-48 (-331)	-28 (-193)	-24 (-165)	-50 (-345)
440C SS	1	-110 (-758)	-130 (-896)	-36 (-248)	-50 (-345)
	4	-88 (-607)	-82 (-565)	-58 (-400)	-62 (-427)
	7	-86 (-593)	-82 (-565)	-56 (-386)	-50 (-345)
AISI 1018	1	+25 (+172)	+20 (+138)	-27 (-186)	-12 (-83)
	4	0	+8 (+55)	+8 (+55)	-14 (-97)
	7	-14 (-97)	-2 (-14)	+8 (+55)	+30 (-207)
P20	1	-10 (-69)	-20 (-138)	-28 (-193)	-18 (-124)
	4	-12 (-83)	-12 (-83)	-28 (-193)	-20 (-138)
	7	-22 (-152)	-16 (-110)	-26 (-179)	-21 (-145)
S5	1	-4 (-28)	-16 (-110)	-16 (-110)	-40 (-276)
	4	-12 (-83)	-14 (-97)	-30 (-207)	-42 (-290)
	7	-26 (-179)	-10 (-69)	-20 (-138)	-18 (-124)
A6	1	+16 (+110)	+12 (+83)	0	+2 (+14)
	4	+20 (+138)	+18 (+124)	0	0
	7	-18 (-124)	-16 (-110)	-34 (-234)	-30 (-207)
A8	1	-8 (-55)	-8 (-55)	0	-16 (-110)
	4	-12 (-83)	-4 (-28)	+4 (+28)	+4 (+28)
	7	+6 (+41)	+4 (+28)	-50 (-345)	-50 (-345)
4130	1	-26 (-179)	-24 (-165)	-30 (-207)	-22 (-152)
	4	-26 (-179)	-22 (-152)	-34 (-234)	-45 (-310)
	7	-26 (-179)	-30 (-207)	-28 (-193)	-40 (-276)
4140	1	-18 (-124)	-26 (-179)	-30 (-207)	-30 (-207)
	4	-24 (-165)	-24 (-165)	-32 (-221)	-30 (-207)
	7	-26 (-179)	-28 (-193)	-16 (-110)	-20 (-138)
Vascomax 200	1	-44 (-303)	-52 (-359)	-90 (-621)	-110 (-758)
	4	-22 (-152)	-60 (-414)	-86 (-593)	-58 (-400)
	7	-50 (-345)	-84 (-579)	-98 (-676)	-84 (-579)
Vascomax 250	1	-145 (-1000)	-74 (-510)	-160 (-1103)	-158 (-1089)
	4	-70 (-483)	-60 (-414)	-80 (-552)	-75 (-517)
	7	-42 (-290)	-50 (-345)	-67 (-462)	-30 (-207)
Vascomax 300	1	-70 (-483)	-56 (-386)	-48 (-331)	-40 (-276)
	4	-70 (-483)	-20 (-138)	-46 (-317)	-18 (-124)
	7	-36 (-248)	-60 (-414)	-12 (-83)	-32 (-221)
Vascomax 350	1	-52 (-359)	-72 (-496)	-6 (-41)	-16 (-110)
	4	-62 (-427)	0	-10 (-69)	+14 (+97)
	7	-90 (-621)	-48 (-331)	-12 (-83)	-26 (-179)

Table 9 Continued. Residual Surface Stress on Welded Blocks

Residual Surface Stress (kpsi) (MPa)					
Position 3		Position 4		Position 5	
X	Y	X	Y	X	Y
-13 (-90)	-16 (-110)	-48 (-331)	0	-36 (-248)	-72 (-496)
+2 (+14)	-14 (-97)	-10 (-69)	-14 (-97)	-48 (-331)	-52 (-359)
-2 (-14)	-12 (-83)	0	-22 (-152)	-22 (-152)	-10 (-69)
-34 (-234)	-26 (-179)	-25 (-172)	-30 (-207)	-50 (-345)	-42 (-290)
-8 (-55)	-18 (-124)	-10 (-69)	-18 (-124)	-2 (-14)	-20 (-138)
+10 (+69)	+8 (+55)	-4 (-28)	-10 (-69)	0	+4 (+28)
-20 (-138)	-26 (-179)	-36 (-248)	-20 (-138)		
-26 (-179)	-28 (-193)	-52 (-359)	-8 (-55)		
-14 (-97)	-16 (-110)	-50 (-345)	-36 (-248)		
-54 (-372)	-42 (-290)	-100 (-689)	-20 (-138)		
-32 (-221)	-22 (-152)	-88 (-607)	-52 (-359)		
-38 (-262)	-30 (-207)	-40 (-276)	-90 (-621)		
-40 (-276)	-38 (-262)	+18 (+124)	-21 (-145)	0	-32 (-221)
-2 (-14)	-22 (-152)	0	-8 (-55)	+20 (+138)	+5 (+35)
+18 (+124)	+10 (+69)	+24 (+165)	+14 (+97)	+8 (+55)	-10 (-69)
-12 (-83)	-22 (-152)	-18 (-124)	-30 (-207)	-12 (-83)	-18 (-124)
-23 (-159)	-18 (-124)	-20 (-138)	-18 (-124)	-38 (-262)	-36 (-248)
-48 (-331)	-34 (-234)	-20 (-138)	-23 (-159)	-30 (-207)	-30 (-207)
-24 (-165)	-36 (-248)	-6 (-41)	-16 (-110)	-20 (-138)	-18 (-124)
-2 (-14)	-16 (-110)	-28 (-193)	-34 (-234)	-18 (-124)	-20 (-138)
-4 (-28)	-2 (-14)	0	+18 (+124)	-6 (-41)	+15 (+103)
+22 (-152)	-2 (-14)	+2 (+14)	-12 (-83)	+27 (+186)	+10 (+69)
+12 (+83)	+4 (+28)	0	+4 (+28)	-20 (-138)	-14 (-97)
-70 (-483)	-75 (-517)	-22 (-152)	-20 (-138)	-68 (-469)	-60 (-414)
+10 (+69)	+4 (+28)	-16 (-110)	-18 (-124)	+22 (+152)	+20 (+138)
+12 (+83)	+16 (+110)	0	+6 (+41)	-3 (-21)	+5 (+35)
+18 (+124)	+26 (+179)	-42 (-290)	-42 (-290)	+14 (+97)	-3 (-21)
-22 (-152)	-24 (-165)	-30 (-207)	-18 (-124)	-20 (-138)	-22 (-152)
-20 (-138)	-24 (-165)	-32 (-221)	-16 (-110)	-15 (-103)	-28 (-193)
-18 (-124)	-27 (-186)	-26 (-179)	-22 (-152)	-22 (-152)	-28 (-193)
-16 (-110)	-22 (-152)	-32 (-221)	-26 (-179)	-22 (-152)	-30 (-207)
-20 (-138)	-34 (-234)	-28 (-193)	-28 (-193)	-18 (-124)	-22 (-152)
-16 (-110)	-15 (-103)	-23 (-159)	-22 (-152)	-18 (-124)	-20 (-138)
-24 (-165)	-50 (-345)	-65 (-448)	-82 (-565)	-30 (-207)	-54 (-372)
-52 (-359)	-18 (-124)	-94 (-648)	-82 (-565)	-52 (-359)	-85 (-586)
-64 (-441)	-42 (-290)	-26 (-179)	-88 (-607)	-46 (-317)	-72 (-496)
-170 (-1172)	-140 (-965)	-106 (-731)	-210 (-1448)	-110 (-758)	-190 (-1310)
-94 (-648)	-68 (-469)	-82 (-565)	-62 (-427)	-110 (-758)	-105 (-724)
-54 (-372)	-34 (-234)	-96 (-662)	-42 (-290)	-55 (-379)	-40 (-276)
-36 (-248)	-32 (-221)	-54 (-372)	-40 (-276)	-53 (-365)	-80 (-552)
-60 (-414)	-8 (-55)	-36 (-248)	-10 (-69)	-46 (-317)	-62 (-427)
-2 (-14)	-26 (-179)	-34 (-234)	-32 (-221)	-60 (-414)	-102 (-703)
-16 (-110)	-16 (-110)	-4 (-28)	-30 (-207)	-30 (-207)	-62 (-427)
-22 (-152)	+4 (+28)	-24 (-165)	-18 (-124)	-60 (-414)	-64 (-441)
-20 (-138)	-24 (-165)	-26 (-179)	-22 (-152)	-22 (-152)	-28 (-193)

Figure 5. Mold Temperature Response to a 100°F (56°C) Change in Oil Temperature

Figure 6. Ramp Rate Versus Insert Thickness

The test data from the medium channel insert set can be used to provide a measure of cooling rate versus channel distance to the surface of the mold. When $(T_1 - T_2)/t$ for the dry cycle experiments is plotted against the channel thickness to the thermocouples, a linear curve, as shown in Figure 6, is found to exist. This rate of temperature change is inversely proportional to the channel-to-surface thickness and decreases by approximately 20°F/minute/inch (0.42°C/minute/mm) of thickness increase. The channel-to-surface thickness range was within 1 to 3 inches (25.4 to 76.2 mm).

ACCOMPLISHMENTS

Maraging steels, especially alloys 200 and 250, were selected as the best for mold applications because of the following properties: deep hardening, low distortion, high toughness, high strength, no weld preheat, easy welding, good quality welds, simple heat-treat requirements (hardened by simple aging process), good quality surface finishes (machined, ground, and EDM), and corrosion resistance. But maraging steels have limited availability and can be purchased only in limited sizes making these alloys impractical except for small mold applications.

Alloys H13, Viscount 44, 420 SS, A6, and A8 are considered acceptable for mold applications with the following properties: deep hardening, low distortion, good toughness, high strength, and good quality surface finishes. Alloys 420 SS and A8 are corrosion resistant; but H13, Viscount 44, and A6 have tendencies to corrode. The primary disadvantages of these five alloys include high weld pre-heat temperature, extensive heat-treat requirements (annealing and hardening), and poorer quality welds (cracks or pores). More emphasis is needed in the area of welding rod selection. Some strength in the weld may have to be sacrificed to obtain ductility necessary to weld without cracking problems.

Surface stress determinations did not correlate with weld quality. Residual surface stress is primarily dependent upon surface finishing.

The medium channel insert set of the oil loop channel design was evaluated for cooling rate and surface temperature gradients. The cooling rate was found to increase from 9 to 29°F/minute (5 to 17°C/minute) for the approximately 1-inch (25.4 mm) variation in channel-to-surface thickness. This rate of temperature change is inversely proportional to the channel-to-surface thickness and decreases by approximately 20°F/minute/inch (0.42°C/minute/mm) of thickness increase.

FUTURE WORK

Future work on this endeavor will be conducted on process engineering account 041233-31. This work includes completion of oil loop design evaluation and analysis of mold alloys, fabrication methods, and crack resistance.

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Appendix

COMPOSITION AND STRENGTH PROPERTIES OF ALLOYS

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Appendix

COMPOSITION AND STRENGTH PROPERTIES OF ALLOYS

H13 Tool Steel

Chemical Composition:

0.35 C, 5.0 Cr, 1.5 Mo, 1.0 V, 0.35 Mn, 1.10 Si.

Yield Strength 0.2 Percent Offset:

100 to 200 kpsi (0.689 to 1.52 GPa) [160 kpsi (1.1 GPa) at R_C 40].

Tensile Strength:

140 to 260 kpsi (0.97 to 1.79 GPa) (170 kpsi) (1.2 GPa).

Elongation:

18 to 12 percent (14 percent).

Viscount 44 Tool Steel

Chemical Composition:

0.40 C, 5.00 Cr, 1.00 V, 1.00 Si, 0.30 Mn, 1.20 Mo.

Yield Strength 0.2 Percent Offset:

100 to 220 kpsi (0.689 to 1.52 GPa) [160 kpsi (1.1 GPa) at R_C 40].

Tensile Strength:

140 to 260 kpsi (0.97 to 1.79 GPa) (170 kpsi) (1.2 GPa).

Elongation:

18 to 12 percent (14 percent).

420 SS

Chemical Composition:

0.15 C (min), 13.0 Cr (min), 1.00 Mn (max), 0.04 P (max), 0.03 S (max), 1.00 Si (max).

Yield Strength 0.2 Percent Offset:

185 to 215 kpsi (1.275 to 1.48 GPa) [215 kpsi (1.48 GPa) at R_C 52].

Tensile Strength:

225 to 250 kpsi (1.55 to 1.72 GPa) (250 kpsi).

Elongation:

8 to 7 percent (8 percent).

440C SS

Chemical Composition:

1.10 C, 17.0 Cr, 1.00 Mn (max), 0.04 P (max), 0.03 S (max), 1.00 Si (max), 0.75 Mo (max).

Yield Strength 0.2 Percent Offset:

220 to 290 kpsi (1.52 to 1.99 GPa) [275 kpsi (1.896 GPa) at R_C 57].

Tensile Strength:

250 to 310 kpsi (1.72 to 2.14 GPa) (285 kpsi) (1.97 GPa).

Elongation:

2 to 0 percent (2 percent).

AISI 1018 Low-Carbon Steel

Chemical Composition:

0.18 C, 0.75 Mn.

Yield Strength 0.2 Percent Offset:

32 to 50 kpsi (0.22 to 0.34 GPa) [40 kpsi (0.28 GPa) at R_b 70].

Tensile Strength:

58 to 75 kpsi (0.40 to 0.52 GPa) (60 kpsi) (0.41 GPa).

Elongation:

40 to 25 percent (30 percent).

P20 Tool Steel

Chemical Composition:

0.35 C, 1.00 Cr, 0.40 Mo, 0.40 Si, 0.85 Mn.

Yield Strength 0.2 Percent Offset:

105 to 220 kpsi (0.72 to 1.52 GPa) [165 kpsi (1.14 GPa) at R_C 40].

Tensile Strength:

115 to 250 kpsi (0.79 to 1.72 GPa) (180 kpsi) (1.24 GPa).

Elongation:

25 to 8 percent (16 percent).

Be-Cu Alloy 170

Chemical Composition:

1.9 Be, 0.10 Co, balance Cu.

Yield Strength 0.2 Percent Offset:

125 to 155 kpsi (0.86 to 1.1 GPa) [145 kpsi (0.999 GPa) at R_c 38].

Tensile Strength:

150 to 180 kpsi (1.03 to 1.24 GPa) (170 kpsi) (1.17 GPa).

Elongation:

10 to 4 percent (4 percent).

S5 Tool Steel

Chemical Composition:

0.55 C, 0.40 Mo, 0.80 Mn, 2.00 Si, 0.25 Cr, 0.20 V.

Yield Strength 0.2 Percent Offset:

125 to 280 kpsi (0.86 to 1.9 GPa) [170 kpsi (1.17 GPa) at R_c 40].

Tensile Strength:

145 to 340 kpsi (0.999 to 2.34 GPa) (190 kpsi) (1.3 GPa).

Elongation:

22 to 5 percent (18 percent).

A6 Tool Steel

Chemical Composition:

0.70 C, 1.00 Mo, 1.00 Cr, 2.00 Mn, 0.30 Si.

Yield Strength 0.2 Percent Offset:

240 to 305 kpsi (1.65 to 2.1 GPa) [240 kpsi (1.65 GPa) at R_c 50].

Tensile Strength:

260 to 345 kpsi (1.79 to 2.38 GPa) (260 kpsi) (1.79 GPa).

Elongation:

5 to 1 percent (5 percent).

A8 Tool Steel

Chemical Composition:

0.55 C, 1.25 W, 1.25 Mo, 5.00 Cr.

Yield Strength 0.2 Percent Offset:

240 to 305 kpsi (1.65 to 2.1 GPa) [240 kpsi (1.65 GPa) at R_c 50].

Tensile Strength:

260 to 345 kpsi (1.79 to 2.38 GPa) (260 kpsi) (1.79 GPa).

Elongation:

5 to 1 percent (5 percent).

4130 Low-Alloy Steel

Chemical Composition:

0.30 C, 0.95 Cr, 0.20 Mo, 0.50 Mn, 0.25 Si.

Yield Strength 0.2 Percent Offset:

105 to 175 kpsi (0.72 to 1.21 GPa) [165 kpsi (1.14 GPa) at R_c 40].

Tensile Strength:

125 to 200 kpsi (0.86 to 1.38 GPa) (180 kpsi) (1.24 GPa).

Elongation:

25 to 10 percent (16 percent).

4140 Low-Alloy Steel

Chemical Composition:

0.40 C, 0.95 Cr, 0.20 Mo, 0.90 Mn.

Yield Strength 0.2 Percent Offset:

105 to 175 kpsi (0.72 to 1.21 GPa) [165 kpsi (1.14 GPa) at R_c 40].

Tensile Strength:

125 to 200 kpsi (0.86 to 1.38 GPa) (180 kpsi) (1.24 GPa).

Elongation:

25 to 10 percent (16 percent).

Vascomax Type 200 Maraging Steel

Chemical Composition:

18 Ni, 8.5 Co, 3 Mo, 0.2 Ti.

Yield Strength 0.2 Percent Offset:

190 to 225 kpsi (1.31 to 1.55 GPa) [200 kpsi (1.38 GPa) at R_c 46].

Tensile Strength:

195 to 230 kpsi (1.34 to 1.59 GPa) (215 kpsi) (1.48 GPa).

Elongation: 12 to 6 percent (12 percent)

Vascomax Type 250 Maraging Steel

Chemical Composition:

18 Ni, 8 Co, 5 Mo, 0.4 Ti.

Yield Strength 0.2 Percent Offset:

240 to 265 kpsi (1.65 to 1.83 GPa) [250 kpsi (1.72 GPa) at R_C 49].

Tensile Strength:

245 to 270 kpsi (1.69 to 1.86 GPa) (260 kpsi) (1.79 GPa).

Elongation: 10 to 6 percent (10 percent).

Vascomax Type 300 Maraging Steel

Chemical Composition:

18 Ni, 9 Co, 5 Mo, 0.6 Ti.

Yield Strength 0.2 Percent Offset:

260 to 300 kpsi (1.79 to 2.07 GPa) [280 kpsi (1.93 GPa) at R_C 53].

Tensile Strength:

265 to 305 kpsi (1.83 to 2.1 GPa (290 kpsi) (1.999 GPa).

Elongation:

10 to 52 percent (8 percent).

Vascomax Type 350 Maraging Steel

Chemical Composition:

1.5 Ni, 12.5 Co, 3.5 Mo, 1.8 Ti, 0.15 Al.

Yield Strength 0.2 Percent Offset:

250 to 360 kpsi (1.72 to 2.48 GPa) [355 kpsi (2.45 GPa) at R_C 50].

Tensile Strength:

275 to 370 kpsi (1.896 to 2.55 GPa) (365 kpsi) (2.52 GPa).

Elongation:

10 to 5 percent (10 percent).

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