Machining and Forming Operations for Zirconium

INTRODUCTION

Zirconium is a hard, shiny, grayish white metal. With its superior corrosion resistance capabilities, it has increasingly become the material of choice in the fabrication of chemical processing equipment. For non-nuclear applications, zirconium has two main alloys: ASTM R60702 (Zr 702), which is unalloyed, and ASTM R60705, which is alloyed with 2.0-3.0 percent niobium. The physical and mechanical properties of zirconium are listed in **Table 1**. Additional alloy information may be found at our website, www.corrosionsolutions.com, under the "Tech Resources" menu in the "Product Information" section.

TABLE 1: MECHANICAL PROPERTIES OF ZIRCONIUM

Physical Properties	**Zr 702**	**Zr 705**
ATOMIC NUMBER	40	---
ATOMIC WEIGHT	91.22	---
ATOMIC RADIUS		
(Zero charge)	1.60-1.62	---
(+4 charge)	0.80-0.90	---
DENSITY		
(g/cc at 20°C)	6.510	6.640
(lbs/cubic inch)	0.235	0.240
CRYSTAL STRUCTURE		
Alpha Phase	Hexagonal Close-Packed (below 865C)	---
Beta Phase	Body-Centered Cubic (above 865C)	Body-Centered Cubic (above 854C)
Alpha+Beta Phase	---	Hexagonal Close-Packed + Body Centered Cubic (below 854C)
MELTING POINT	1852°C (3365°F)	1840°C (3344°C)
BOILING POINT	4377°C (7910°F)	4380°C (7916°C)
COEFFICIENT OF THERMAL EEEXPANSION (per °C at 25C/73F)	5.89×10^{-6}	6.3×10^{-6}
SPECIFIC HEAT		
(BTU / lb / F)	0.068	0.067
VAPOR PRESSURE(mmHg)		
At 2000°C (3632°F)	0.01	---
At 3600°C (6512°F)	900.0	---

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ELECT. RESISTIVITY		
ohm-cm at 20C (68°F)	39.7	55.0
TEMP. COEFFICIENT OF		
per °C at 20C (68°F)	0.0044	---
LATENT HEAT OF FUSION (Cal /gm)	60.4	---
LATENT HEAT OF VAPORIZATION (Cal /gm)	1550	---
Mechanical Properties		
MODULUS OF ELASTICITY (psi)	14.4×10^6	14.0×10^6
SHEAR MODULUS (psi)	5.25×10^6	5.0×10^6
POISSON'S RATIO	0.35	0.33

The ductility and workability of zirconium allows standard shop equipment to be used for machining and forming operations, with few modifications or new techniques required. There are, however, some special considerations that need to be made when working with zirconium. The information here will provide a starting point for less experienced fabricators, or those working with zirconium for the first time, listing guidelines, recommendations, and specific data when applicable.

MACHINING OPERATIONS

There are three basic principles that should be followed when machining zirconium: slow speeds, high feed rates, and a flood coolant system using a water-soluble oil lubricant. Zirconium does tend to gall and work-harden, which requires higher than normal clearance angles on tools to penetrate the work-hardened surface and cut a clean coarse chip.

In most cases, both carbide and high-speed steel tools give satisfactory results when machining zirconium; however, carbide will usually allow higher productivity and give a better finish. Performance is greatly enhanced by keeping the tools sharp. It is also important to prevent the accumulation of fine chips, since zirconium can be pyrophoric; small machine chips or turnings with a high surface-area-to-mass ratio are easily ignited and burn at extremely high temperatures (see Safety section). Information for specific operations are given below:

Turning

There are no special requirements for turning zirconium. It can be done without difficulty using standard equipment, as long as sharp tools and a coolant lubricant are used. Recommended operating parameters are given in **Tables 2 and 3**. Lead angles on tools should be between +15 and +60 degrees.

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TABLE 2: SINGLE POINT TURNING OF ZIRCONIUM

Carbide Tool					High Speed	
DEPTH OF CUT in (mm)	**TOOL MATERIAL AISI (ISO)**	**SPEED fpm (m/min)**	**FEED ipr (mm/r)**	**TOOL MATERIAL AISI (ISO)**	**Steel Tool SPEED Fpm (m/min)**	**FEED ipr (mm/r)**
0.040	C-2	275-325	0.007	M2, M3	150	0.007
0.150	C-2	225-265	0.015	M2, M3	100	0.015
0.300	C-2	175-200	0.020	M2, M3	80	0.020
(1.0)	(K20, M20)	(84-100)	(0.18)	(S4, S5)	(46)	(0.18)
(4.0)	(K20, M20)	(69-81)	(0.40)	(S4, S5)	(30)	(0.40)
(8.0)	(K20, M20)	(53-60)	(0.50)	(S4, S5)	(24)	(0.50)

TABLE 3: CUTOFF AND FORM TOOL TURNING OF ZIRCONIUM

TOOL	**SPEED**	**Cutoff Tool Width**			**FEED ipr (mm/r) Form Tool Width**				
AISI (ISO)	fpm (m/m)	.062 in (1.5mm)	.125in (3mm)	.250in (6mm)	.500 in (12mm)	.750 in (18mm)	1.00 in (25mm)	1.50 in (35mm)	2.00 in (50mm)
T15, M42	65	.002	.0025	.003	.003	.0025	.0025	.002	.002
C-2	190	.002	.0025	.003	.003	.0025	.0025	.002	.002
(S9, S11)	(20)	(.050)	(.063)	(.075)	(.075)	(.063)	(.063)	(0.050)	(0.050)
(K40, M40)	(58)	(.050)	(.063)	(.075)	(.075)	(.063)	(.063)	(0.050)	(0.050)

Milling

Both vertical face and horizontal slab milling of zirconium give good results. Whenever possible, zirconium should be climb milled to penetrate the work at the maximum approach angle and depth of cut while emerging through the work-hardened area. It is important that the milling cutters be kept very sharp and the work area flooded or sprayed with coolant to completely wash away the chips from the tool. Specific operating set points for milling zirconium are given in **Tables 4-9**. Lead angles on tools should be between +15 and +30 degrees, with positive axial and positive radial rake angles.

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TABLE 4: FACE MILLING OF ZIRCONIUM

Carbide Tool					**High Speed Steel Tool**	
DEPTH OF CUT in (mm)	TOOL MATERIAL AISI (ISO)	SPEED fpm (m/min)	FEED per TOOTH in (mm)	TOOL MATERIAL AISI (ISO)	SPEED fpm (m/min)	FEED per TOOTH ipr (mm/r)
0.040	C-2	285-350	0.006	M2, M3	175	0.006
0.150	C-2	235-290	0.010	M2, M3	115	0.010
0.300	C-2	190-225	0.014	M2, M3	90	0.014
(1.0)	(M20)	(87-105)	(0.15)	(S4, S2)	(53)	(0.15)
(4.0)	(M20)	(72-88)	(0.25)	(S4, S2)	(35)	(0.25)
(8.0)	M20)	(56-69)	(0.36)	(S4, S2)	(27)	(0.36)

TABLE 5: SLAB MILLING OF ZIRCONIUM

		Carbide Tool	
DEPTH OF CUT in (mm)	TOOL MATERIAL AISI (ISO)	SPEED fpm (m/min)	FEED per TOOTH in (mm)
0.040	M2, M7	125	0.006
0.150	M2, M7	80	0.008
0.300	M2, M7	65	0.010
(1.0)	(S4, S2)	(38)	(0.15)
(4.0)	(S4, S2)	(24)	(0.20)
(8.0)	(S4, S2)	(20)	(0.25)

TABLE 6: HOLLOW MILLING OF ZIRCONIUM

TOOL MATERIAL	**SPEED**	**FEED**
AISI or C (ISO)	fpm (m/min)	ipr (mm/r)
M2, M7	75	0.004
C-2	180	0.008
(S4, S2)	(23)	(0.102)
(K20)	(55)	(0.20)

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TABLE 7: SIDE AND SLOT MILLING OF ZIRCONIUM

Carbide Tool					High Speed Steel Tool	
DEPTH OF CUT in (mm)	TOOL MATERIAL AISI (ISO)	SPEED fpm (m/min)	FEED per TOOTH in (mm)	TOOL MATERIAL AISI (ISO)	SPEED fpm (m/min)	FEED per TOOTH ipr (mm/r)
0.040	C-2	400-480	0.007	M2, M7	175	0.006
0.150	C-2	350-420	0.008	M2, M7	165	0.007
0.300	C-2	250-300	0.009	M2, M7	150	0.008
(1.0)	(M20)	(120-145)	(0.18)	(S4, S2)	(53)	(0.15)
(4.0)	(M20)	(105-130)	(0.20)	(S4, S2)	(50)	(0.18)
(8.0)	(M20)	(76-90)	(0.23)	(S4, S2)	(46)	(0.20)

TABLE 8: THREAD MILLING OF ZIRCONIUM

TOOL MATERIAL AISI or C (ISO)	**SPEED** fpm (m/min)	**FEED** in/tooth/rev (mm/tooth/rev)
M2, M7	115	0.002
(S4, S2)	(35)	(0.050)

TABLE 9: END MILLING OF ZIRCONIUM

AXIAL DEPTH	**TOOL**	**SPEED**	**FEED in/tooth (mm/tooth) Width of Slot**			
In (mm)	AISI (ISO)	fpm	3/8 in	1/4 in	3/4 in (18mm)	1-2 in (25-50mm)
0.030	T15, M42	125	.0015	.002	.0025	.003
0.125	T15, M42	100	.002	.0025	.003	.004
dia/2	T15, M42	75	.0015	.002	.0025	.003
dia/1	15, M42	60	.0007	.001	.002	.0025
(0.75)	(S9, S11)	(38)	(.038)	(.050)	(.063)	(.075)
(3.0)	(S9, S11)	(30)	(.050)	(.063)	(.075)	(.102)
(dia/2)	(S9, S11)	(23)	(.038)	(.050)	(.063)	(.075)
(dia/1)	(S9, S11)	(18)	(.018)	(.025)	(.050)	(.063)

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Drilling

Good results for drilling zirconium can be achieved using the standard fresh ground (118°) thin webbed drill and a coolant lubricant. It is important to use a firm backing to prevent burrs at the exit. Also, ensuring a sufficient amount of stock material is left for reaming can minimize smearing. Tapping zirconium is done best using chip driver or gun type taps, they must be kept sharp.

TABLE 10: DRILLING OF ZIRCONIUM

		FEED ipr (mm/r) Nominal Hole Diameter							
TOOL	**SPEED**								
AISI or C	fpm	1/16 in	1/8 in	1/4 in	1/2 in	3/4 in	1 in	1-1/2 in	2 in
(ISO)	(m/min)	(1.5mm)	(3mm)	(6mm)	(12mm)	(18mm)	(25mm)	(35mm)	(50mm)
M10, M7, M1	55	.002	.003	.004	.006	.008	.010	.012	.015
(S2, S3)	(17)	(.050)	(.075)	(.102)	(.15)	(.20)	(.25)	(.30)	(.40)

TABLE 11: BORING OF ZIRCONIUM

Carbide Tool					**High Speed Steel Tool**	
DEPTH OF CUT in (mm)	TOOL MATERIAL AISI (ISO)	SPEED fpm (m/min)	FEED per TOOTH in (mm)	TOOL MATERIAL AISI (ISO)	SPEED fpm (m/min)	FEED per TOOTH ipr (mm/r)
0.010	C-2	240-280	0.003	M2, M3	150	0.003
0.050	C-2	190-225	0.005	M2, M3	120	0.005
0.100	C-2	155-185	0.012	M2, M3	80	0.012
(0.25)	(K20, M20)	(73-85)	(0.075)	(S4, S5)	(46)	(0.075)
(1.25)	(K20, M20)	(58-69)	(0.13)	(S4, S5)	(37)	(0.13)
(2.5)	(K20, M20)	(47-56)	(0.30)	(S4, S5)	(24)	(0.30)

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TABLE 12: TAPPING OF ZIRCONIUM

TOOL MATERIAL	**SPEED**			
	fpm (m/min) **Threads per inch**			
	7 or less	8-15	16-24	over 24
	(Pitch – mm)			
AISI (ISO)	(over 3)	(1.5-3)	(1-1.5)	(1 or less)
M10, M7, M1	45	75	95	100
(S2, S3)	(14)	(23)	(29)	(30)

TABLE 13: REAMING OF ZIRCONIUM

		FEED					
TOOL	**SPEED**	**ipr (mm/r) Reamer Diameter**					
AISI or C (ISO)	Fpm (m/min)	1/8 in (3mm)	1/4 in (6mm)	1/2 in (12mm)	1 in (25mm)	1-1/2 in (35mm)	2 in (50mm)
M1, M2, M7	55	.005	.008	.012	.018	.020	.025
C-2	175	.004	.007	.010	.016	.020	.025
(S2, S3, S4)	(17)	(.13)	(.20)	(.30)	(.45)	(.50)	(.65)
(K20)	(53)	(.102)	(.18)	(.25)	(.40)	(.50)	(.65)

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Grinding Both wheel grinding and belt grinding can be used for zirconium. For wheel grinding, conventional speeds and feeds are satisfactory with silicon carbide wheels giving better results than aluminum oxide. The effect of grinding fluid on zirconium is the same as on other metals; grinding oils alone produce higher grinding ratios than water miscible fluids, which means less wheel breakdown and finer finishes. Recommended operating set-points are given in **Tables 14-17**.

In belt grinding zirconium, belt speed and contact wheel selection are the key considerations. Contact wheels should be relatively hard and aggressive. Soluble oil coolants alone, or mixed with water and applied in a flood, are recommended. Resin abrasive cloth may be used with oil and rubber contact wheels on general polishing operations, while Resin Industrial Cloth Type 3 or Type 6 are recommended for use with oil in grinding operations where high grinding pressures are used. Similarly, waterproof cloth silicon carbide for light work and aluminum oxide for heavy work may be effectively employed with soluble oil and water coolants.

TABLE 14: SURFACE GRINDING OF ZIRCONIUM

WHEEL SPEED	**TABLE SPEED**	**DOWNFEED**	**CROSSFEED**	**WHEEL IDENTIFICATION**
fpm (m/s)	fpm (m/min)	in/pass (mm/pass)	in/pass (mm/pass)	ANSI (ISO)
3000	40	Rough: 0.001 Finish: 0.0005 max	0.040 – 0.400 max=1/6 of wheel width	C46JV
(15)	(12)	(Rough: 0.025) (Finish: 0.013 max)	(1.0 – 10.0) (max=1/6 of wheel width)	C46JV

TABLE 15: CYLINDRICAL GRINDING OF ZIRCONIUM

WHEEL SPEED fpm (m/s)	WORK SPEED fpm (m/min)	INFEED On Diameter in/pass (mm/pass)	TRAVERSE wheel width per revolution of work	WHEEL IDENTIFICATION ANSI (ISO)
3000	60 – 100	Rough: 0.001 Finish: 0.0005 max	1/6 – 1/12	C60KV or CA60PB
(15)	(18 - 30)	(Rough: 0.025) (Finish: 0.013max)	(1/6 – 1/12)	(C60KV or CA60PB)

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TABLE 16: INTERNAL GRINDING OF ZIRCONIUM

WHEEL SPEED fpm (m/s)	WORK SPEED fpm (m/min)	INFEED On Diameter in/pass (mm/pass)	TRAVERSE wheel width per revolution of work	WHEEL IDENTIFICATION ANSI (ISO)
3000	50 – 150	Rough: 0.0005 Finish: 0.0002 max	1/3 – 1/6	C80KV
(15)	(18 - 30)	(Rough: 0.013) (Finish: 0.005max)	(1/3 – 1/6)	(C80KV)

TABLE 17: CENTERLESS GRINDING OF ZIRCONIUM

WHEEL SPEED fpm (m/s)	THRUFEED OF WORK On Diameter in/min (m/min)	INFEED in/pass (mm/pass)	WHEEL IDENTIFICATION ANSI (ISO)
3000	50 – 150	Rough: 0.001 Finish: 0.0005 max	Rough: A60TB or CA60 RB Finish: CA80PB
(15)	(1.3 – 3.8)	(Rough: 0.025) (Finish: 0.013 max)	(Rough: A60TB or CA60 RB) (Finish: CA80PB)

Sawing

Power hacksawing is done most efficiently with coarse (3T) high speed steel blades using a medium stroke rate and a light feed rate. Band sawing is generally done with a saw having a 0.042-inch raker set and a saw width of 0.50 inch, in conjunction with a flood of soluble lubricant or an air stream to wash away the chips from the cut to give satisfactory results. For cold circular sawing, teeth should be alternately leveled and square, with the leveled teeth slightly higher than the square. The cut and the saw blades should be cooled with soluble coolant. Fine chips should be removed from the area frequently to prevent a build-up of flammable solids. Sawing data recommendations are shown in **Tables 18-20**.

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TABLE 18: POWER HACK SAWING OF ZIRCONIUM

MATERIAL THICKNESS in (mm)	TEETH PER INCH pitch in (mm)	SPEED strokes/min (strokes/min)	FEED in/stroke (mm/stroke)	PRESSURE
< .25	10	125	0.15	Medium
.25 - .75	6	125	0.15	Medium
.75 - 3	4	115	0.15	Medium
> 2	4	115	0.15	Medium
(< 6)	(2.5)	(125)	(0.15)	(Medium)
(6 – 18)	(2.5)	(125)	(0.15)	(Medium)
(18 - 50)	(4)	(115)	(0.15)	(Medium)
(> 50)	(4)	(115)	(0.15)	(Medium)

TABLE 19: BAND SAWING OF ZIRCONIUM

MATERIAL THICKNESS in (mm)	TOOTH FORM	TEETH PER INCH pitch (mm)	BAND SPEED fpm (m/min)
< .50	precision	10 - 14	100
.50 - 1	precision	8 - 10	90
1 – 3	precision	6 – 8	75
> 3	claw, precision	3 – 4	6 5
(<12)	(precision)	(2.5 – 1.8)	(30)
(12 – 25)	(precision)	(3 – 2.5)	(27)
(25 – 75)	(precision)	(4 – 3)	(23)
(>75)	(claw, precision)	(8.5 – 6.3)	(20)

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TABLE 20: CIRCULAR SAWING OF ZIRCONIUM

STOCK DIAMETER OR THICKNESS in (mm)	TOOL MATERIAL AISI (ISO)	PITCH in/tooth (mm/tooth)	SPEED fpm (m/min)	FEED in/tooth (mm/tooth)
.25 - 3	M2, M7	0.20 – 0.75	60	0.008
3 – 6	M2, M7	0.50 – 1.10	50	0.008
6 – 9	M2, M7	0.75 – 1.30	40	0.010
9 – 15	M2, M7	0.90 – 1.75	30	0.010
(6 – 80)	(S2, S4)	(5 – 20)	(18)	(0.20)
(80 – 160)	(S2, S4)	(12 – 30)	(15)	(0.20)
(160 – 250)	(S2, S4)	(20 – 35) (12)	(0.25)	

FORMING OPERATIONS

Although zirconium can be formed using standard shop equipment, it does have a tendency to react with gases in the air at elevated temperatures and to gall and seize under sliding contact with other metals. A thin oxide layer, acting as a lubricant, protects against galling in forming operations. If additional lubricant is needed, use any oil or grease that does not contain halogen or sulfur (with the exception of molydisulfide).

A. Bending

Sheet or strip zirconium can be easily bent on conventional press brake or roll forming equipment to a 5T bend radius at room temperature and to 3T at approximately 200°C. For cold forming zirconium tube, a minimum bend radius of 3 times the OD dimension is advisable. For smaller radius bends, hot forming at temperatures from 200°C to 425°C or the use of special bending techniques is required. When bending zirconium tube, spring back may be encountered due to its work hardening behavior. Also, both the inside and outside surfaces at the bend area must be in tension during any bending operation to prevent buckling and wall thinning.

B. Punching

Zirconium requires high plate pressures or excessive side flow occurs during punching operations. Very close punch and die tolerances, 1 to 2 percent of the metal thickness, provide the best results. It is essential that the dies remain sharp when punching zirconium. There is a tendency for zirconium to build up on the punch sides thus making stripping difficult. A die lubricant will minimize galling and reduce die wear.

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C. Drawing and Spinning

Despite its work hardening characteristics, zirconium's formability by hot and cold operations is good. Designs that eliminate severe or abrupt section changes, and allow generous radii are a must. Dies of non-galling material with tolerances and clearances comparable to those used for austenitic stainless steels should be employed. As in the case of tube bending, die designs should allow for the spring back tendency of the material.

SAFETY

There is one major precaution that must be considered when working with zirconium. It is non-toxic, but because of its very high heat-producing reaction with oxidizing elements such as oxygen, zirconium is pyrophoric. Large pieces of sheet, plate, bar, tube, and ingot can be heated to high temperatures without burning, however, small machine chips and filings are easily ignited and will burn at extremely high temperatures. Therefore, it is necessary to prevent large accumulations of chips or other small pieces of zirconium, and care should be taken to store this material in non-flammable containers and isolated areas. Zirconium chips and filings should be frequently cleared from machines and moved to a proper storage container. An effective method of storage for zirconium chips and filings is to keep the material covered with water in the containers, with a layer of oil on top of the water to prevent evaporation. It is important to keep any storage container covered to prevent stray sparks from igniting the zirconium. If a fire does start in zirconium, ordinary fire extinguishers or water must not be used. Only dry sand, powdered graphite or special Metal-X powder should be used.

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