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White Paper

Performance Materials

Designing and Working with Heavily Loaded Bushings Made From ToughMet Alloy

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ABSTRACT

Materion's ToughMet® alloys are spinodally hardened copper-nickel-tin alloys that have proven success in thrust bearings, journal/plain/sleeve bearings and linear sliding bearings. This paper presents a series of recommendations to allow you to get the most out or your bushing/bearing design.

PART 1: DESIGNING WITH TOUGHMET ALLOYS

As a "drop-in" replacement for other bronze or steel plain bushings, bushings made from ToughMet material can have a longer lifespan, withstand higher loads and employ a wider range of lubrication options.

This paper describes how to design, machine and run grease-lubricated journal bushings made from ToughMet alloy, while highlighting material-specific requirements such as permissible loads, mating material hardness, interference fit, clearances and machining considerations.

These bushings can be designed in a manner very similar to bronze bushings. Interference fit (in a housing) and clearance for the pin can be calculated the same as those for standard bronze bushings. ToughMet Alloy bushing tolerancing calculations can be found in Appendix C. Please note: Bushing designs often evolve over time to accommodate material inadequacies. With ToughMet alloys, consider the original spirit of the design.

CONTINUOUS MAXIMUM LOAD

Using a ToughMet alloy as a replacement for standard bronze bushings, it is possible to apply a higher load over an equivalent area or to reduce the contact area under the existing load. The maximum dynamic load in cases of limited motion, as determined by the galling threshold, ranges from approximately 70-100 ksi (480-690 MPa) for most hardened steels coupled with ToughMet alloys. As determined by their compressive strength, the maximum static load ToughMet alloys can withstand is 110 ksi (760 MPa). PV limit testing of ToughMet 3 alloy indicates that it can be used at values in excess of 375,000 psi sfm (9.6 MPa m/s).

Note that ToughMet alloys are ideal bearing materials at high loads and low speeds. When running at high speeds or at higher temperatures, the starting clearance needs to be increased. The shaft can only expand outward due to thermal expansion. Since the steel housings around the bearing are cooler and stiffer, thermal expansion forces the bearing to expand inward, which can reduce or even eliminate the clearance entirely. Under these circumstances, softer bronze alloys will quickly wear and increase the clearance again, while the stronger ToughMet alloys will work harden and impede motion if the designed clearance is not increased appropriately to account for thermal expansion.

MATING MATERIALS AND SURFACES

To ensure preferential wear on the ToughMet alloy bushing and minimize wear on both materials, choose a mating surface material with minimum hardness of 40 HRC (approximately 400 HV) for ToughMet 3 alloy or 34 H-RC (330 HV) for ToughMet 2 alloy. Softer materials will be preferentially worn by the ToughMet material. While these are absolute minimum hardnesses, Materion strongly recommends a hardness of 60 HRC (700 HV) or higher. This will ensure the steel remains smooth and does not cause excessive wear on the ToughMet alloy. Suitable mating materials include hardened carbon steel, precipitation hardened stainless steels, chrome plated steels, etc.

The optimum surface finish for the mating material is below 10 μ inches (0.25 μm) running against ToughMet alloy with surface roughness below 16 μ inches (0.40 μm). For heavily loaded, slower moving joints, a mating surface roughness of 32 μ inches (0.81 μm) against a ToughMet alloy surface roughness of 64 μ inches (1.6 μm) is acceptable. In any case, the mating surface should be smoother than the ToughMet alloy. The harder, smoother mating surface will wear-in the ToughMet material, polishing and work hardening it. The near-surface hardness of ToughMet alloy after work hardening is typically 36 HRC (350 HV). See section on wear-in for further information.

PLANNING INTERFERENCE FIT

ToughMet alloys are often inserted into the housing via press fit or shrink fit methods. For a press-fit, a housing surface roughness of approximately 32 μ inches (0.81 μm) against the ToughMet alloy surface may assist in the method. It is acceptable to use liquid nitrogen or refrigeration, for example, at -40°F/-40°C for a shrink fit. ToughMet alloy has a lower elastic modulus than that of steel, which reduces the holding force of the interference fit. To correct for the difference when substituting ToughMet alloy for steel, increase the interference fit by 50%. For optimal performance, Materion recommends boring after installation to obtain needed cylindricity and clearance tolerance. This is especially important when two or more bushings reside on the same pin, to limit the effect of 'stacking' tolerances to maintain shaft alignment.

The recommended minimum interference fit is 0.04% (i.e. the diameter of the bushing OD should be 0.04% larger than the diameter of the housing bore). For ToughMet alloys, the upper limit for interference can be as high as 0.4%; however, such a large interference may not be feasible with a shrink fit. With a CTE of 9.6×10^{-6} per degree F (17.3×10^{-6} per degree C), a dry ice/alcohol bath will shrink ToughMet 3 alloy ~0.09% and liquid nitrogen will shrink it by 0.3%. It should be determined if the housing can withstand the stress created by higher levels of interference. Per ANSI class FN2 guidelines, cast iron housings should not be used in fits with an interference exceeding 0.28%. The ANSI Class FN2 force fit as well as the ISO H7/s6 fit per ISO 286-2 are acceptable fits for bushings in steel housings.

If ToughMet material is press fit into a housing, the approximate force needed at full insertion is given by:

$$F(tons) \approx 65 \times interference(\%) \times Wall_{Thickness}(in.) \times Length(in.)$$

$$F(tons) \approx 1/11 \times interference(\%) \times Wall_{Thickness}(mm) \times Length(mm)$$

This calculation assumes a thick-walled, steel housing and a friction coefficient of 0.1. A thinner housing or lower modulus housing will require less force. This insertion force may limit the maximum interference.

For smaller sizes, the machining tolerance will dictate the maximum interference.

BUSHING BORE SHRINKAGE FROM INTERFERENCE

During a shrink or force fit of a bushing made from ToughMet alloy into a housing with an interfering fit, the inner diameter (ID) of the bushing is reduced. In the case of a thin-walled bushing in a thick-walled steel housing, the ID of the bushing will shrink 85% of the diametrical interference. When ToughMet alloy is placed in a housing of lower modulus, or thinner wall, the amount of shrink will be substantially smaller. Approximate factors for this are given in Appendix C: Table 1. In the case of a cylindrical bushing fit in a cylindrical housing, a good estimate of the ID shrinkage can be made with an application of the Lamé equation. Actual shrinkage will be greater at the center than at the edges, due to edge effects for which the Lamé equation does not account. Also, if the bore is not centered in the housing, the resultant forces on the bushing from interference may result in a bushing ID that is out of round. The actual shrink would need to be modeled by FEA methods. In-line boring after installation is strongly recommended to maintain roundness, straightness and radial tolerances.

CLEARANCE AND ELEVATED TEMPERATURE CONSIDERATIONS

The running clearance between a bushing made from ToughMet alloy and a mating pin is system specific. A good starting point is the H7/f6 non-ferrous standard fit from ISO 286-2. Be sure to include shrinkage in the bushing ID due to interference fits (see previous section). Like other bronzes, ToughMet alloy has a higher coefficient of thermal expansion compared to that of steel. Care should be taken to prevent loss of clearance in higher temperature applications or those with a wide temperature range as the two mating materials may expand at differing rates. Typically a steel pin will be used, so the clearance may increase at elevated temperature if the bushing is free to expand.

The inside diameter of a bushing made from ToughMet alloy confined in a steel housing may decrease at elevated temperature due to thermal expansion and result in the loss of clearance. If there is a potential for high temperatures in operation, the initial clearance should be expanded to avoid the potential for clearance flipping to interference.

BEARING/SHAFT ALIGNMENT

Unlike softer bronze alloys, ToughMet alloys will not quickly yield and conform to the shaft when used in a misaligned bearing. ToughMet alloys are stronger and more wear resistant, so they will not change shape to accommodate misalignment. Misalignment can use up all the available clearance and result in galling or seizing. This is especially true when there are multiple bearings on one shaft. In this case, line boring after installation will ensure that the bearings are properly aligned with the shaft.

LUBRICATION GROOVES

Because ToughMet alloy works well in heavily-loaded boundary lubricated situations, fewer grooves can be used maximizing the bearing surface and reducing contact pressure. In some cases, grooves can be eliminated altogether. Grooves are best placed with some portion of the length perpendicular to the direction of motion[1]. Lubrication can be fed through either the "pin" or the bushing. The Cast Bronze Bearing Design Manual[3] is a good resource for further information on groove design.

PART 2: WORKING WITH TOUGHMET ALLOY

TOUGHMET ALLOY STOCK FINISHING ALLOWANCES

Each form and temper of ToughMet material has different finishing allowances. Please refer to Appendix A to find the correct ordering size. A Materion customer service representative can help determine appropriate dimensions.

MACHINING RECOMMENDATIONS

ToughMet alloys are typically a short chip copper alloy and machines very well, especially when aided with chip breakers. ToughMet alloys should be machined in the "as-received" condition, with a harder grade of carbide to minimize wear. Grade C5 is recommended for most applications. Chip breakers incorporated into the insert aid in producing a very short, manageable chip. Surface finishes finer than 100 micro inches (2.5 microns) Ra are possible with feeds as large as 0.004 inch (0.1 mm) per revolution. Liquid coolant is recommended. Positive rake angles are strongly recommended.

Milling is best performed with a carbide-inserted milling cutter. The same cutters used for P20 tool steels can be employed; however, a positive rake angle is advantageous.

ToughMet alloy tends to work harden during machining. Use deep but diminishing cuts to remove the work hardened layer from previous passes. Worn tooling can impart significant residual stress while still keeping the final parts within geometric tolerance, so it is important to keep the tooling sharp and flood with liquid cooling to minimimze thermal stresses. Residual stress can result in significant distortion, especially when bushings and bearings are split after machining.

Appendix B suggests recommended machining parameters for ToughMet alloys. These parameters are conservative values based on simple machining studies. Variations of these may be necessary depending on part geometry and available machine tools.

For machining of thin-walled bushings, the minimum achievable tolerance by conventional machining practices is given by:

$$tolerance = \frac{length}{wall_{Thickness}} \times 0.0001 in.$$

To achieve a smaller tolerance, additional processes such as grinding or honing should be considered. Care must be taken to understand the effect of the fixturing (e.g. three jaw chuck, arbor, etc.) on the free state dimensions of the bushing. Aggressive material removal, especially on open contour designs, can impart machining stresses into the material, causing 'movement' when removed from the machining constraints. Using 'diminishing' cuts and sharp tools may help alleviate this situation. Please consult with the Materion Customer Technical Service Department.

Machining burrs can be detrimental to ToughMet alloy's performance in tighter tolerance situations. Special features, such as chamfers or a radius, should be cut in a direction opposite to the bushing surface, so any burrs would be located at the end (and away from the contact surface).

SCRAP

Chips can also be mixed and sold with other copper alloy scrap. Materion offers a premium for clean, segregated ToughMet alloy scrap. Call +1-419-862-4233 or your local agent for details.

PART 3: RUNNING WITH TOUGHMET ALLOY

BUSHING OPERATING LUBRICANTS

ToughMet alloy is compatible with most oils and greases. There is no need for a special lubricant. ToughMet alloy has also been run with water, salt water, graphite and mild soap solutions as lubricant.

WEAR-IN

Under heavily-loaded conditions, there is a very brief initial period where the ToughMet alloy surface work hardens, increasing by about 6 HRC pts. There may be a small material transfer of ToughMet alloy to the mating surface. This transfer does not measurably affect the diameter of the pin or the clearance between the two surfaces, nor is it any indication of failure. This transfer is a one-time process, and period of time depends upon speeds and pressures in the system. If the system is disassembled, and the material transfer cleaned, wear-in will happen again when reassembled. (Actual system wear can be tested as any other bronze: change in wall thickness, increase in clearances or observation of copper-contaminated lubricant.)

FURTHER INFORMATION

For additional literature, further information or technical assistance on alloy properties or processing of ToughMet alloys, contact Materion's Customer Technical Services Group at +1.800.375.4205 (+1.216.692.3108).

REFERENCES:

1. Strand, Henrik (2005). *Design, Testing and Analysis of Journal Bearings for Construction Equipment (Doctoral Thesis).* KTH Royal Institute of Technology. http://kth.divaportal.org/smash/record.jsf?pid=diva2:11656

2. Tomoshenko, Stephen P., Goodier, J.N. (1970). *Theory of Elasticity.* McGraw-Hill, 70.

3. Ripple, Harry C. (1993). *Cast Bronze Bearing Design Manual.* Copper Development Association Inc.

APPENDIX A: ORDERING STOCK TOUGHMET ALLOY

TABLE 1

Allowances for Ordering ToughMet Alloy CX Tempers Rod/Tube

Finished Size	Add to Outside Diameter for "Order Size"
Up to and including 9" (229 mm) OD	0.125" (3.2 mm)
Over 9" (229 mm) OD	0.225" (5.7 mm)

TABLE 2

Outside Diameter Allowances for Ordering AT/TS Rod and Tube

Finished Size	Add to Outside Diameter for "Order Size"
Up to and including 7" (178 mm) OD	0.060" (1.5 mm)
Over 7" (178 mm) OD	0.125" (3.2 mm)

APPENDIX B: MACHINING TOUGHMET ALLOY

Note: Mil measurements refer to one thousandth of an inch.

The speeds presented are for ToughMet 2 CX90, ToughMet 3 CX110 and ToughMet 3 AT110 tempers. The speeds for softer tempers can be increased in proportion to the reduction of yield strength. It is recommended to hold feeds to the same value.

TABLE 3
Turning

Alloy	Tool Material	Surface Speed		Roughing Feed at Depth		Finishing Feed	
		(sfm)	(m/min)	(mil/rev)	(mm/rev)	(mil/rev)	(mm/rev)
ToughMet 2 CX	HSS C2 (K20) Carbide	200-500 300-3000	60-150 90-900	6-10 @ 0.050" 6-20 @ 0.10"	0.15-0.25 @ 1.3 mm 0.15-0.5 @ 2.5 mm	2–5 @ 0.025" 2–5 @ 0.030"	0.05-0.15 @ 0.6 mm 0.05-0.15 @ 0.75 mm
ToughMet 3 CX	HSS C5 (P40) Carbide	50 400-800	15 120-240	1-2 @ 0.050" 5-12 @ 0.10"	0.025-0.05 @ 1.3 mm 0.13-0.3 @ 2.5 mm	1-2 @ 0.010" 2-4 @ 0.010"	0.025-0.05 @ 0.25 mm 0.05-0.10 @ 0.25 mm
ToughMet 3 AT	HSS C5 (P40) Carbide	50 400-800	15 120-240	1-2 @ 0.050" 5-12 @ 0.10"	0.025-0.05 @ 1.3 mm 0.13-0.3 @ 2.5 mm	1-2 @ 0.010" 2-4 @ 0.010"	0.025-0.05 @ 0.25 mm 0.05-0.10 @ 0.25 mm

TABLE 4
Milling

Alloy	Tool Material	Surface Speed		Roughing Feed		Finishing Feed	
		(sfm)	(m/min)	(mil/tooth)	(mm/tooth)	(mil/tooth)	(mm/tooth)
ToughMet 2 CX	HSS C2 (K20) Carbide	200-500 300-3000	60-150 90-900	3-5 @ 0.050" 6-20 @ 0.10"	0.075-0.13 @ 0.05 mm 0.15-0.50 @ 2.5 mm	2-5 @ 0.010" 2-5 @ 0.025"	0.05-0.13 @ 0.25 mm 0.05-0.13 @ 0.65 mm
ToughMet 3 CX	HSS C5 (P40) Carbide	100 300-500	30 90-250	1-3 @ 0.050" 5-15 @ 0.125"	0.025-0.075 @ 1.3 mm 0.13-0.40 @ 3 mm	1-2 @ 0.015" 2-4 @ 0.010"	0.025-0.05 @ 0.40 mm 0.05-0.10 @ 0.25 mm
ToughMet 3 AT	HSS C5 (P40) Carbide	100 300-500	30 90-150	1-3 @ 0.050" 5-15 @ 0.125"	0.025-0.075 @ 1.3 mm 0.13-0.40 @ 3 mm	1-2 @ 0.015" 2-4 @ 0.010"	0.025-0.05 @ 0.40 mm 0.05-0.10 @ 0.25 mm

TABLE 5
Drilling and Tapping

Alloy	Tool Material	Surface Speed		Feed		Tapping Speed	
		(sfm)	(m/min)	(mil/rev)	(mm/rev)	sfm	(m/min)
ToughMet 2 CX	HSS C2 (K20) Carbide	100-300 300-3000	30-90 90-900	10-20 6-20	0.25-0.50 0.15-0.50	15 15	4.50 4.50
ToughMet 3 CX	Cobalt Steel C5 (P40) Carbide	50 150-500	15 45-150	2-10 5-20	0.05-0.25 0.13-0.50	10 10	3 3
ToughMet 3 AT	Cobalt Steel C5 (P40) Carbide	50 150-500	15 45-150	2-10 5-20	0.05-0.25 0.13-0.50	10 10	3 3

TABLE 6
Grinding and Sawing

Alloy	**Grinding**			**Sawing**				
	Grinding Wheel Type	Wheel Speed		Saw Blade		Blade Type	Blade Speed	
		(sfm)	(m/min)	(tpi)	(mm/tooth)	(mm/tooth)	(fpm)	(m/min)
ToughMet 2 CX ToughMet 3 CX ToughMet 3 AT	A54LV	5500-6500	1700-2000	1.20 / 1.80	18-12.50	Variable Pitch Carbide Tipped Blade	80	25

APPENDIX C: TOUGHMET ALLOY BUSHING TOLERANCING WORKSHEET

1. Nominal bore diameter (inches):	L1	
Enter design dimension.		
2. Minimum interference of housing and bushing (inches):	L2	
		= 0.0004 x L1
3. Tolerance of interference fit (sum of ISO 286-2 IT Grades 6 & 7):	L3	
Enter sum of tolerance for 6 and 7 band from ISO or ANSI table or use formula provided. Proper units (inches) must be used in formula.		= 0.0013" x [L1 (in.)]$^{0.35}$
4. Minimum housing bore (inches):	L4	
		= L1
5. Maximum housing bore (inches):	L5	
Tolerance on bore is 60% of total tolerance.		= L4 + 0.6 x L3
6. Minimum bushing OD (inches):	L6	
		= L5 + L2
7. Maximum bushing OD (inches):	L7	
Tolerance on the OD is 40% of the total tolerance.		= L6 + 0.4 x L3
8. Nominal shaft OD (inches):	L8	
Enter design dimension.		
9. Expected Temperature Rise (°F)	L9	
10. Expanded Shaft ID (inches)	L10	
		L9 x L8 x 6.8E-6
11. Minimum running clearance (ISO 286-2 shaft limit deviation f) (inches):	L11	
Enter sum of fit limit "f" from ISO or ANSI table or use formula provided. Proper units (inches) must be used in formula.		= 0.00074" x [L8 (in.)]$^{0.43}$
12. Maximum wall thickness (inches)	L12	
		= L4 - (L10 + L11)
13. Bushing ID shrinkage factor due to interference:	L13	
		Enter factor from Table 1 below
14. Radial thermal expansion of bushing (inches)	L14	
		= L12 x L9 x 9.1E-6
15. Maximum bushing ID shrinkage due to interference and thermal expansion (inches):	L15	
		= L13 x (L2 + L3 +L14)
16. Total tolerance for clearance (sum of ISO 286-2 IT Grades 7 & 8) (inches):	L16	
Enter sum of tolerance for 7 and 8 band from ISO or ANSI table or use formula provided. Proper units (inches) must be used in formula.		= 0.002" x [L8 (in.)]$^{0.36}$
17. Variation in interference fit transmitted to the bushing ID (inches):	L17	
		= L13 x L3
18. Tolerance available to machining (inches)	L18	
If calculated value is less than 0.002", set to 0.002".		= L16 - L17
19. Minimum bushing ID (inches):	L19	
		= L10 + L15
20. Maximum bushing ID (inches):	L20	
If tolerance (L20 - L19) on bushing ID is too tight, increase the value on line 18 and recalculate lines 19 through 22.		= L19 + 0.6 x L18
21. Maximum shaft OD (inches)	L21	
		= L8 - L9
22. Minimum shaft OD (inches)	L22	
If tolerance (L20 - L19) on bushing ID is too tight, increase the value on line 14 and recalculate lines 19 through 22.		= L21 - 0.4 x L18

TABLE 7

Fraction of Interference Transmitted to ID of Bushing

This table represents general values. For more precise values, choose the appropriate contour value from the charts below.

Condition	L10
ID bored or machined to size after installation.	0
Thin-walled bushing (< 10% of bushing OD) in heavy-walled (> 50% of bushing OD) steel housing.	0.85
Bushing wall ≈ housing wall (steel only).	0.6
Thin-walled bushing in a heavy-walled aluminum housing.	0.7
Thick-walled bushing (> 30% of bushing OD) in heavy-walled (> 50% of bushing OD) steel housing.	0.5

FIGURE 1

Contours for Bushing ID Shrinkage as % of Interference for ToughMet Bushing in Steel Housing

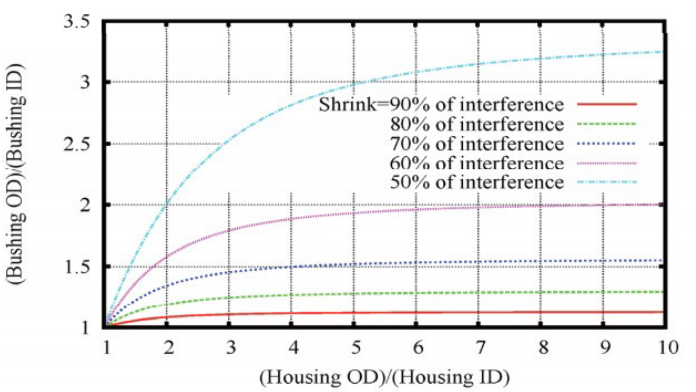
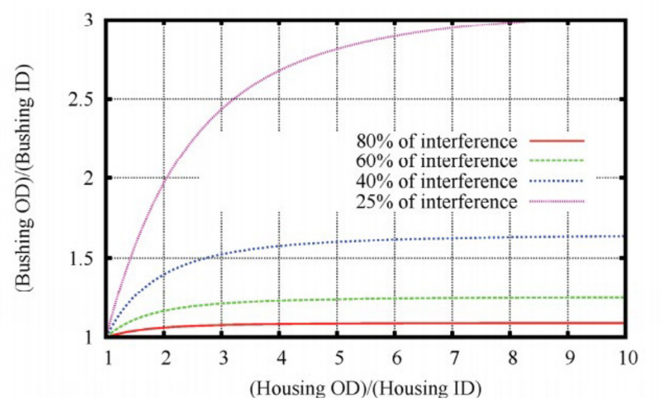


FIGURE 2

Contours for Bushing ID Shrinkage as % of Interference for ToughMet Bushing in Aluminum Housing



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