Testing Report: ToughMet® Alloy Comparison

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Overview

This study was originally conducted at the request of L&H Industrial. It has been reformatted slightly for broader distribution by Materion Corporation.

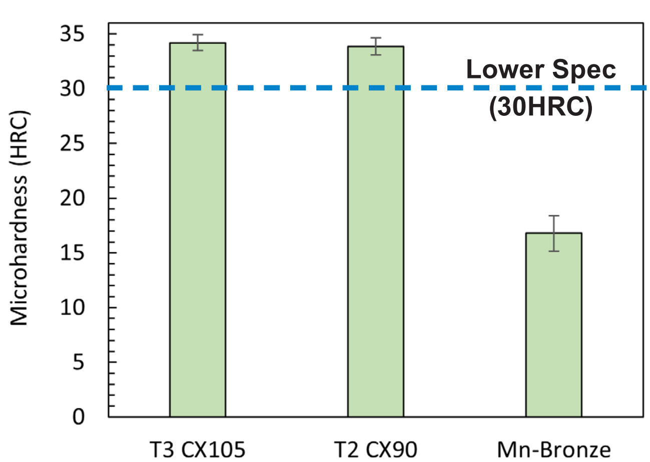
Sample Summary

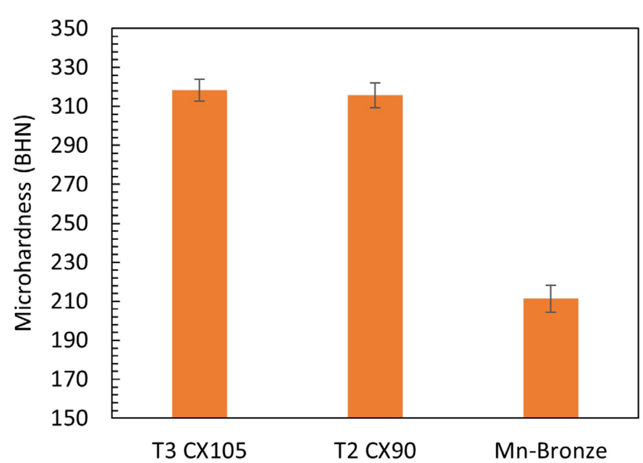
Sample Name	Alloy	Vendor
T3 CX105	ToughMet® 3 CX105 UNS 96900 ASTM B505 Spinodally hardened Cu-15Ni-8Sn alloy	Materion
T2 CX90	ToughMet® 2 CX90 UNS C96970 ASTM B505 Spinodally hardened Cu-9Ni-6Sn alloy	Materion
Mn Bronze	Manganese Bronze UNS C86300	Unknown

The above table summarizes the various specimens evaluated in this report.

Microhardness Analysis

- Vickers microhardness testing was performed on each alloy. A total of 10 tests were performed on each specimen.
- Results showed the Mn Bronze alloy is considerably softer than the T3 CX105 and T2 CX90 alloys.
- Because the hardness for Mn Bronze falls below the conventional Rockwell C scale, the results have also been reported in Brinell Hardness (BHN).
- The hardness values for the Mn Bronze specimens are similar, although slightly lower, than those often reported (~210-230 BHN) for C86300 Mn Bronze alloys.
- Both Materion alloys exhibited hardness higher than the minimum hardness specification (i.e., 30 HRC and 27 HRC for T3 CX105 and CX90, respectively) defined in the Materion material certification.
- The T2 CX90 alloy had comparable average hardness and slightly more hardness variability than the T3 CX105 alloy. This is largely attributed to a single hardness reading (see pages 4-5).
- The average hardness for the T3 CX105 and T2 CX90 material was 34.2 ± 0.7 HRC and 33.6 ± 1.3 HRC, respectively.





Microhardness Analysis

T3 CX105			
Test #	**HV**	**HRC**	**Brinell (BHN)**
1	338.9	34.6	321.4
2	328.8	33.4	311.8
3	346.8	35.4	329.0
4	340.2	34.7	322.6
5	328.8	33.4	311.8
6	333.8	34.0	316.5
7	333.8	34.0	316.5
8	337.6	34.4	320.2
9	329.4	33.5	312.3
10	338.3	34.5	320.8
Average	**335.6**	**34.2**	**318.3**
Stdev	**5.8**	**0.7**	**5.6**

T2 CX90			
Test #	**HV**	**HRC**	**Brinell (BHN)**
1	323.9	32.8	307.1
2	335.1	34.1	317.8
3	331.9	33.7	314.7
4	326.3	33.1	309.4
5	323.3	32.7	306.5
6	332.5	33.8	315.3
7	342.2	34.9	324.6
8	339.6	34.6	322.1
9	338.3	34.5	320.8
10	305.4	30.5	289.4
11	337.0	34.3	319.6
Average	**330.5**	**33.6**	**313.4**
Stdev	**10.5**	**1.3**	**10.0**

MN-Bronze			
Test #	**HV**	**HRC**	**Brinell (BHN)**
1	226	17.9	216.0
2	220.8	16.9	211.4
3	218.7	16.4	209.6
4	208	14.2	200.4
5	229.9	18.7	219.5
6	221.1	16.9	211.7
7	225.3	17.8	215.4
8	228.8	18.5	218.5
9	207.1	14.0	199.6
10	219.7	16.7	210.5
Average	**220.5**	**16.8**	**211.3**
Stdev	**7.8**	**1.6**	**6.8**

Microhardness Analysis

- These tables provide the microhardness measurements for each material.
- Once again, the increased variability of the T2 CX90 material compared to T3 CX105 is largely associated with a single measurement (Test #10) which reduced the average hardness and increased the standard deviation. Without Test #10 the average microhardness for T2 CX90 would be 33.9 ± 0.8 HRC.

Wear Testing - Overview

- Block-on-ring sliding wear testing was performed per ASTM G77.
- Testing details are summarized below.

Category	Description/Details
Test Method	Block-on-Ring (ASTM G77)
Test Block	ToughMet alloy (T3 CX105 and T2 CX90) Surface lapped to 4-8 µin rms
Test Ring	Falex S-10, SAE 4620, Rc 58-63, 6-12 µin rms Conforms to ASTM D2714, D3704 and G77
Tensile Load	100 lb. (444.8 N)
Rotational Speed	100 RPM
Sliding Speed	0.18 m/s (0.6 ft/s)
Lubrication	5w30 motor oil
Sliding Distance	~500 m (~1640 ft)
Revolutions	4,500

Wear Testing - Overview
G77 Block Preparation

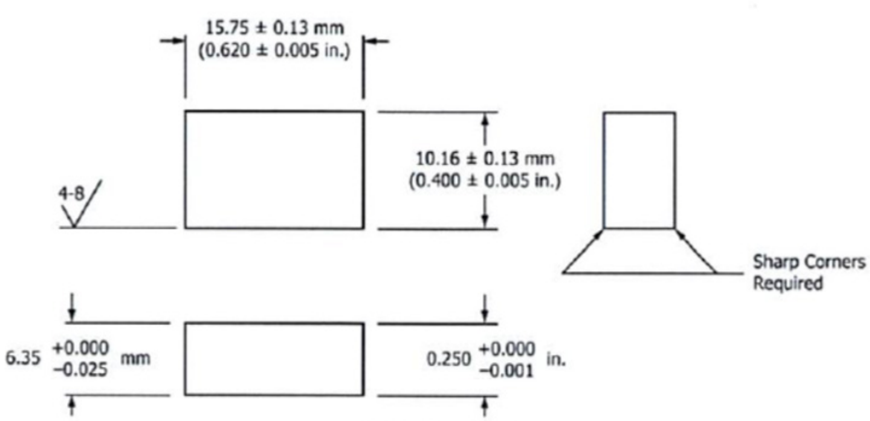


FIG. 3 Test Block

Test blocks were surface lapped (in the direction of sliding) to meet the surface finish requirements (4-8 µin) specified in ASTM G77.

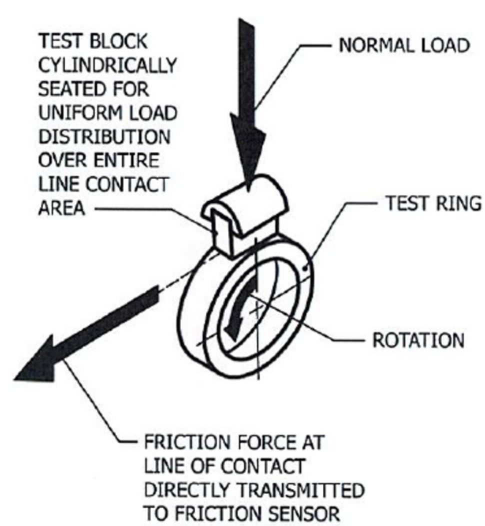


FIG. 1 Test Schematic

Wear Testing - Overview

G77 Block Preparation

Alloy	Sample	Surface Roughness
T3 CX105	1	3.35 µin (0.085 µm)
T3 CX105	2	4.65 µin (0.118 µm)
T3 CX105	3	4.13 µin (0.105 µm)
T2 CX90	1	4.16 µin (0.106 µm)
T2 CX90	2	3.20 µin (0.081 µm)
T2 CX90	3	4.27 µin (0.108 µm)
T2 CX90	4	4.78 µin (0.121 µm)
Mn Bronze	1	3.15 µin (0.080 µm)
Mn Bronze	2	3.06 µin (0.078 µm)
Mn Bronze	3	2.23 µin (0.057 µm)

Wear Testing - Results Summary

- The table below provides an overall summary of the wear testing results.
- The T2 CX90 alloy exhibited slightly lower CoF and CoF variability compared to T3 CX105 specimens.
- Moreover, T2 CX90 exhibited slightly worse sliding wear resistance with larger average wear scar width and wear volume compared to T3 CX105 specimens. Thus, while the T2 CX90 material exhibited similar hardness and a very uniform microstructure (lacking microsegregation) compared to the T3 CX105 material, it exhibits worse wear behavior. This is likely associated with the difference in alloy content for this alloy (much less Ni and Sn). It should be noted that the difference in wear behavior between these alloys is small. Nevertheless, an improvement in wear performance of T3 CX105 would be expected due to the higher alloy content (increased Ni and Sn content).
- The Mn Bronze alloy exhibited considerably more wear compared to the T3 CX105 and T2 CX90 alloys. The reduced wear resistance can be attributed to lower hardness (and strength) for Mn Bronze.

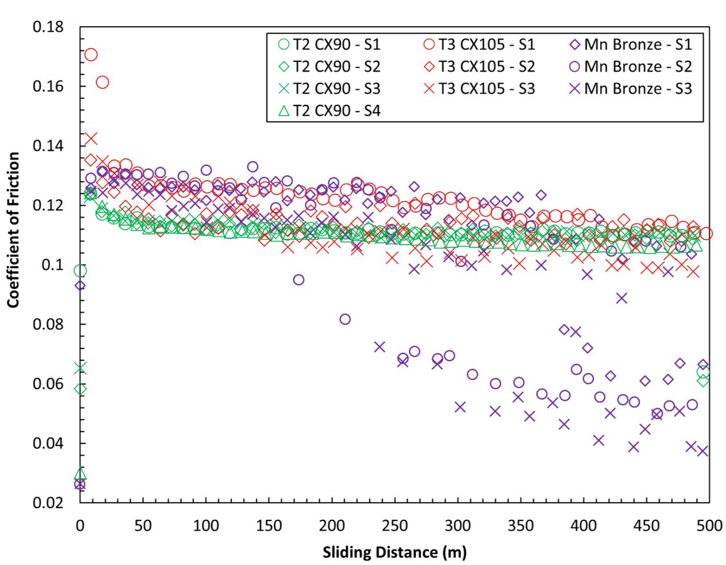
Material	Coefficient of Friction	Scar Width	Scar Volume (mm^3)	Volume Loss (by mass) (mm^3)
T3 CX105	0.112 ± 0.006	2.44 ± 0.18	0.44 ± 0.09	0.42 ± 0.10
T2 CX90	0.110 ± 0.002	2.83 ± 0.22	0.70 ± 0.17	0.71 ± 0.18
Mn Bronze	0.090 ± 0.022	4.35 ± 0.08	2.52 ± 0.08	2.32 ± 0.07

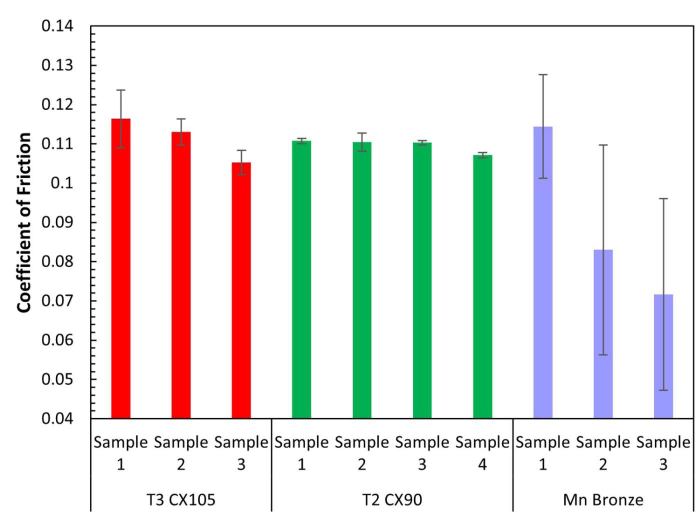
Wear Testing - Coefficient of Friction

- All specimens exhibited a reduction in coefficient of sliding friction (CoF) with increasing sliding distance.
- T3 CX105 and T2 CX90 exhibited statistically similar CoF, however, the T2 CX90 alloy exhibited less CoF variability, both within test and between tests.
- On average, the Mn Bronze alloy exhibited a lower CoF than both Materion alloys. However, this difference is due to the region over which the average CoF is being reported and due to larger CoF variability that occurred after 200 m sliding distance.
- At early time points (<200 m sliding distance) the Mn Bronze alloy exhibited similar CoF to the Materion alloys.

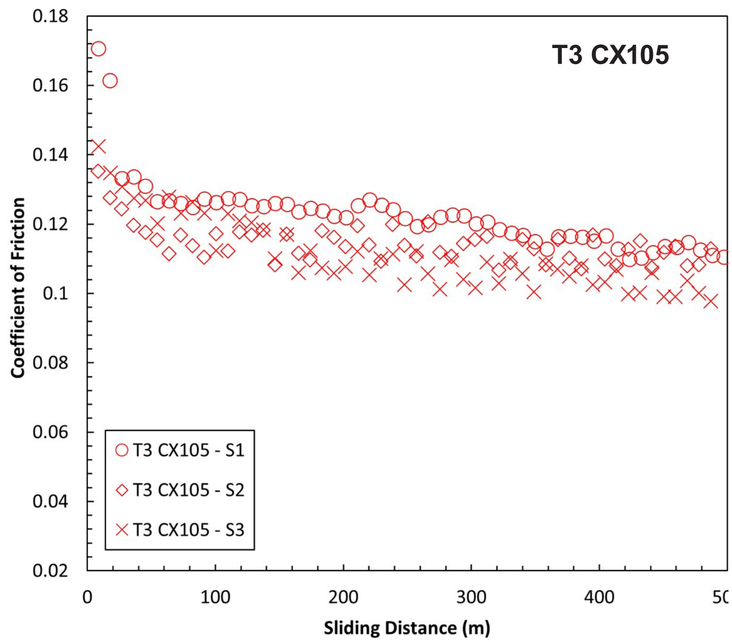
Material	Sample	Coefficient of Friction	
		Average	Stdev
T3 CX105	Sample 1	0.116	0.007
	Sample 2	0.113	0.003
	Sample 3	0.105	0.003
	Avg	**0.112**	**0.005**
	Stdev	**0.006**	**0.002**
T2 CX90	Sample 1	0.111	0.001
	Sample 2	0.110	0.002
	Sample 3	0.110	0.001
	Sample 4	0.107	0.001
	Avg	**0.110**	**0.001**
	Stdev	**0.002**	**0.001**
Mn Bronze	Sample 1	0.114	0.013
	Sample 2	0.083	0.027
	Sample 3	0.072	0.024
	Avg	**0.090**	**0.021**
	Stdev	**0.022**	**0.007**

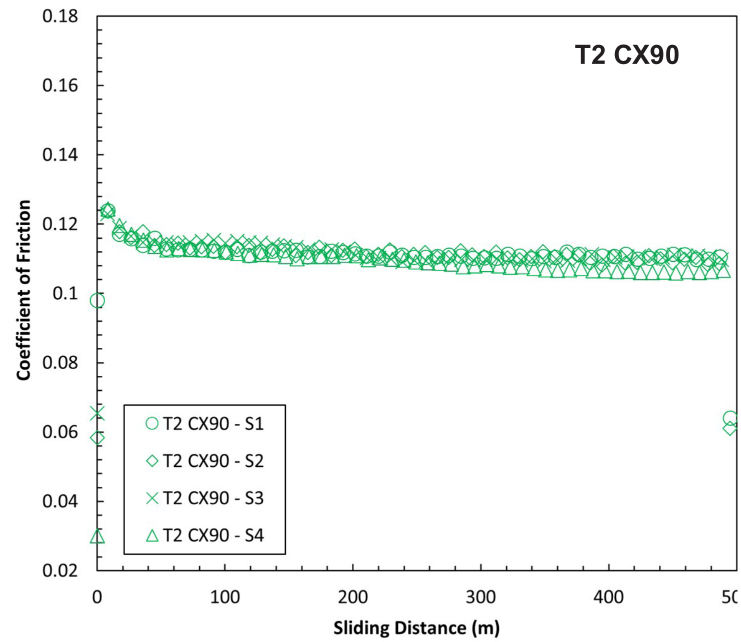
*Avg COF reported for 300-400 m sliding distance.

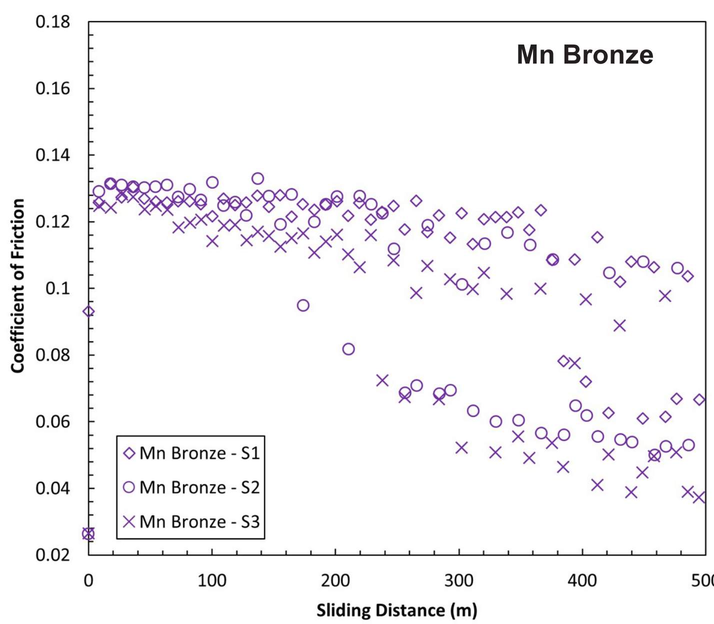




Wear Testing - Coefficient of Friction

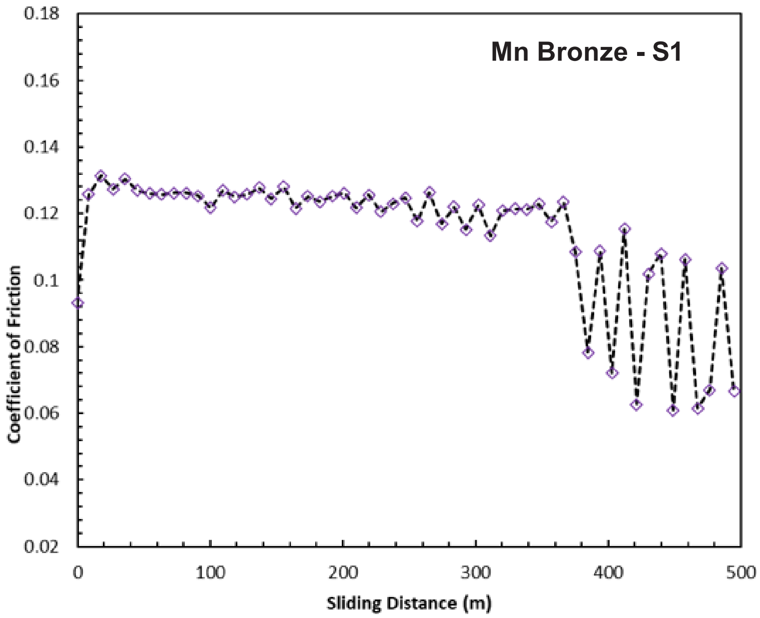


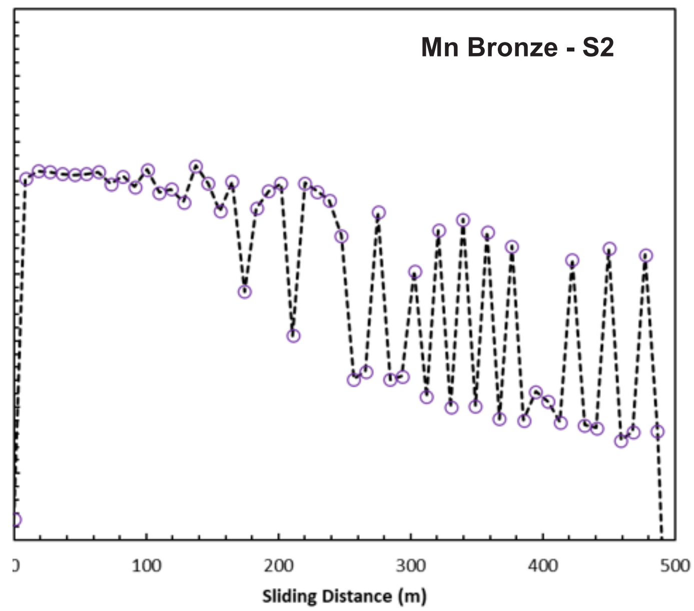


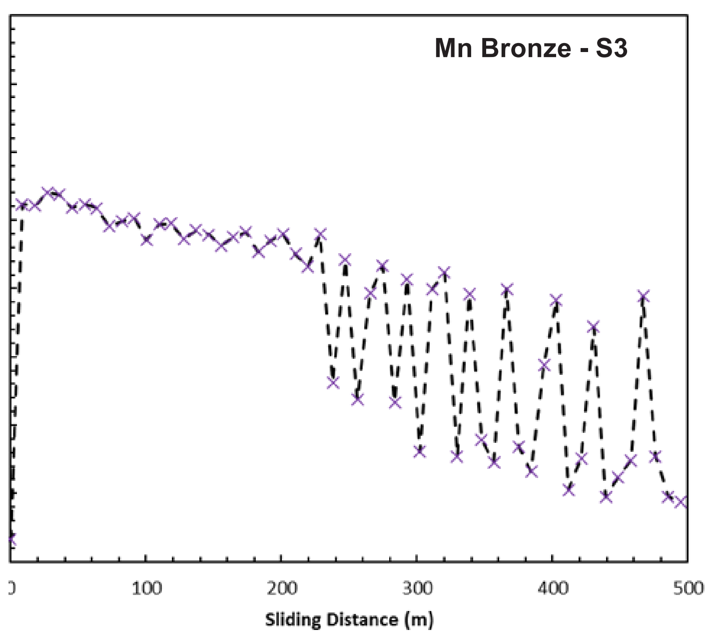


- The above graphs show the COF vs sliding distance data for each alloy.
- Note, the T2 CX90 alloy shows the lowest COF at early sliding distances and a more uniform COF behavior overall (between samples). This observation is not surprising considering this alloy is known for excellent lubricity and is commonly used for low friction bushings and bearings.
- Note, the COF for the Mn Bronze alloys is similar to the Materion alloys at early sliding distances. However, after 200 m of sliding stick-slip behavior began to occur which resulted in considerable variability in the COF behavior.
- Stick-slip behavior will be discussed more on the subsequent page.

Wear Testing - Coefficient of Friction (2)





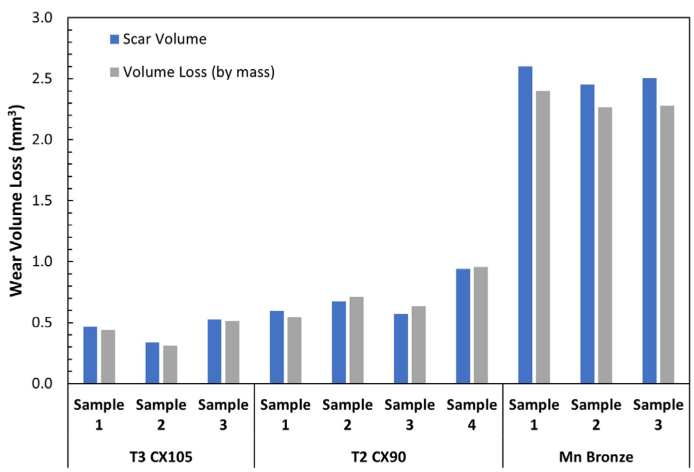


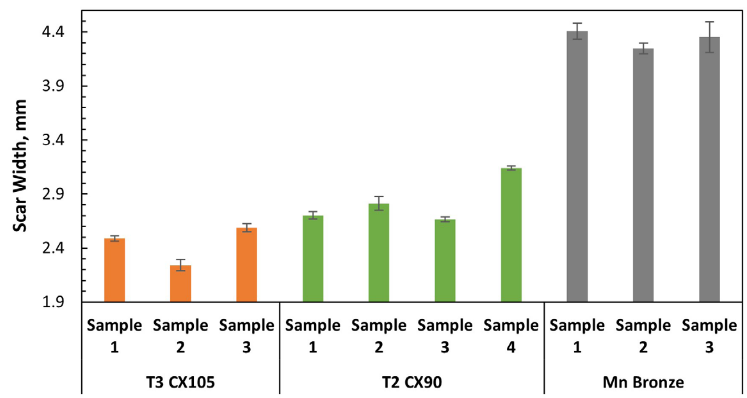
- The CoF versus sliding distance plots for each Mn Bronze specimen are provided above.
- Here the CoF is plotted with a continuous line to demonstrate the slip-stick behavior occurring under sliding wear for this alloy.
- The onset for stick-slip behavior occurred after a sliding distance of 350, 175, and 225 m for Sample 1, 2, and 3, respectively.
- Due to the stick-slip behavior, the average CoF reported (300-400 m sliding distance) previously is artificially low. The real CoF is quite similar to the Materion alloys at earlier sliding distances.

Wear Testing - Wear Volume

- Scar width and depth were measured using a laser scanning confocal microscope (LSCM).
- Per ASTM G77, the total wear scar volume was calculated from the wear scar width. (Scar Volume)
- Total wear volume loss was also calculated by measuring the weight of the test blocks before and after G77 testing. (Volume Loss (by mass))
- Volume loss (by mass) and scar volume measurements are well correlated.

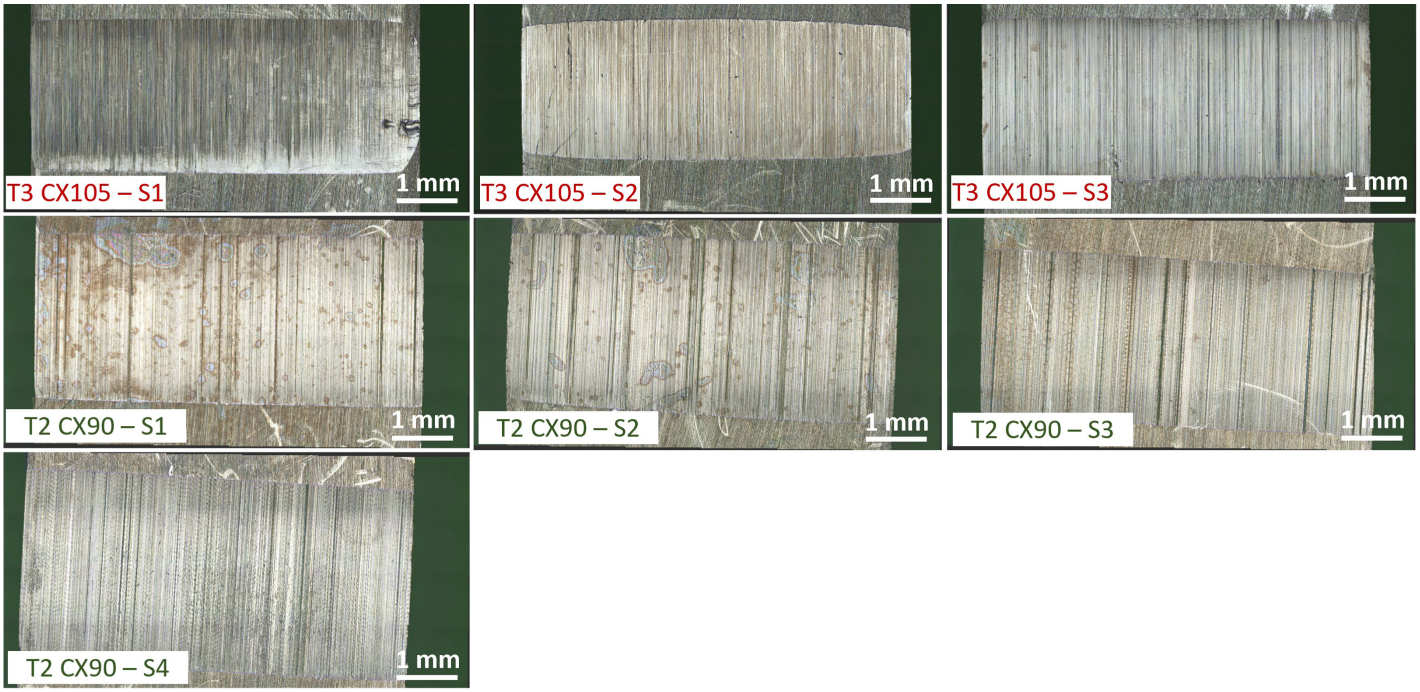
Material	Scar Width	Scar Volume (mm^3)	Volume Loss (by mass) (mm^3)
T3 CX105	2.44 ± 0.18	0.44 ± 0.09	0.42 ± 0.10
T2 CX90	2.83 ± 0.22	0.70 ± 0.17	0.71 ± 0.18
Mn Bronze	4.35 ± 0.08	2.52 ± 0.08	2.32 ± 0.07



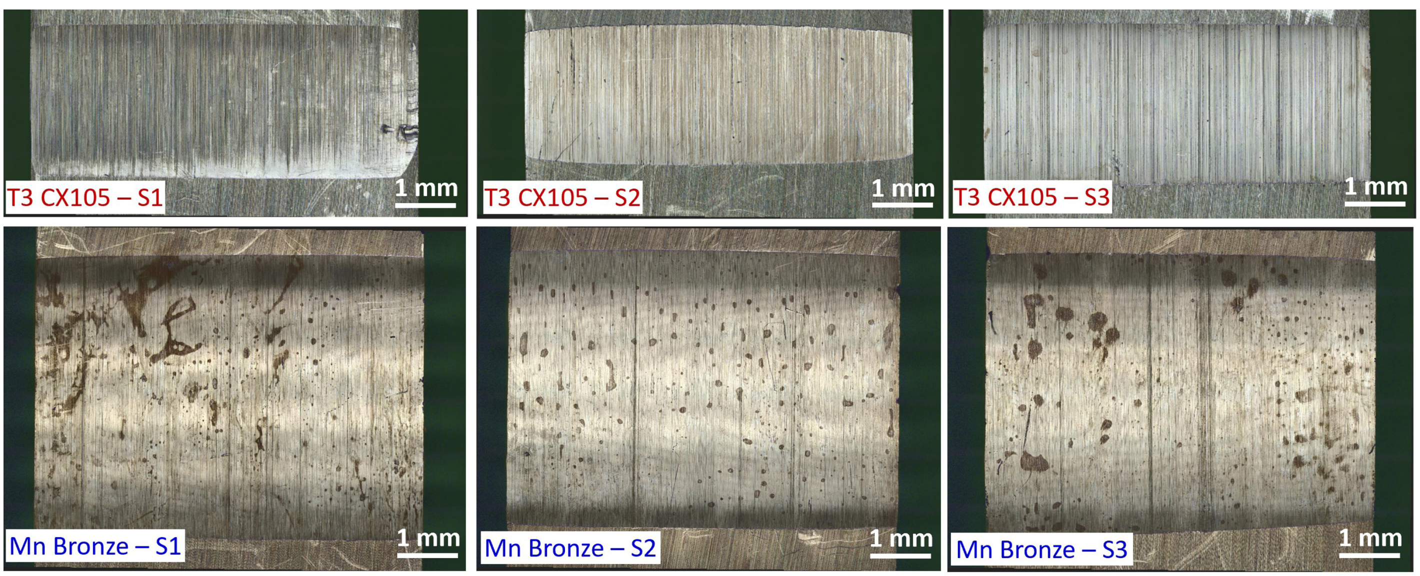


- Results show the Mn Bronze specimens experienced considerably more wear than the T3 CX105 and T2 CX90 alloys. This includes 2-3 times larger wear scar and 4-5 times larger wear volume loss.
- The reduced wear resistance of the Mn Bronze alloy is attributed to reduced hardness (strength) of the alloy.
- The T2 CX90 alloy exhibited a slightly larger average wear scar width and average wear volume compared to the T3 CX105 alloy.
- Reduced wear performance of T2 CX90 compared to T3 CX105 is associated with the reduced alloy content in T2 CX90 and associated reduction in strength. Nevertheless, the difference in wear performance between these two alloys is very small and in some cases is not statistically significant.

Wear Testing - Wear Scar Analysis



- The images above show combined laser/optical micrographs of the wear scar following G77 testing for each wear block for T3 CX105 and T2 CX90 specimens.



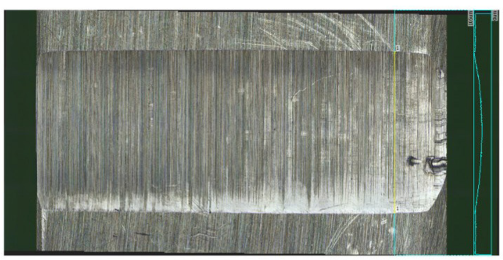
- The images above show combined laser/optical micrographs of the wear scar following G77 testing for each wear block for the T3 CX105 and Mn Bronze specimens. T3 CX105 is provided for visual comparison only.
- Additional discussion is provided on the subsequent page.

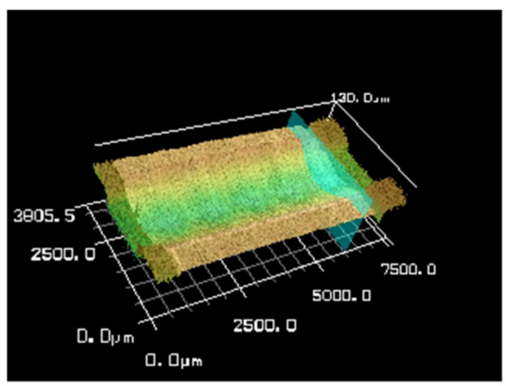
Wear Testing - Wear Scar Analysis

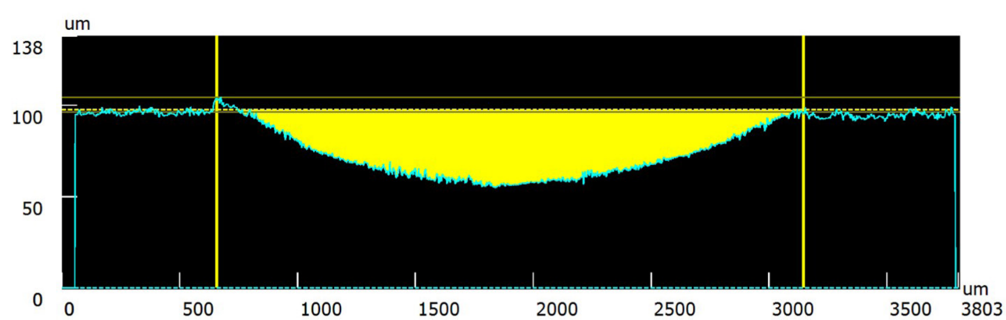
- The previous page provides combined laser/optical micrographs of the wear scar following G77 testing for each wear block.
- Generally, the wear scars appear uniform indicating proper alignment of the block and ring during testing.
- Several T2 CX90 specimens exhibit a wear scar that is orientated such that the scar is not perpendicular to the specimen surface. However, the scar width is generally uniform, thus these tests appear to still be valid.
- Note, wear scar measurements showed that the coefficient of variance (COV) for multiple scar width measurements on each block were well below 10% (per ASTM G77). This indicates that each test is considered a valid test per ASTM G77.
- The T3 CX105 specimen wear scars are generally thinner than the T2 CX90 wear scars.
- Interestingly, both T3 CX105 and T2 CX90 materials have specimens that exhibit much larger scratches within the wear scar. The cause for increased wear scratch sizes is not known at this time.
- Comparing the Mn Bronze wear scars to the T3 CX105 and T2 CX90 specimens, the Mn Bronze specimens exhibit a much larger wear scar. Thus, much more wear was experienced in the Mn Bronze material.
- The subsequent information provides laser scanning confocal microscope (LSCM) data for each test block (1 of 5 measurements provided for brevity).

LSCM Analysis

T3 CX105 - Sample 1





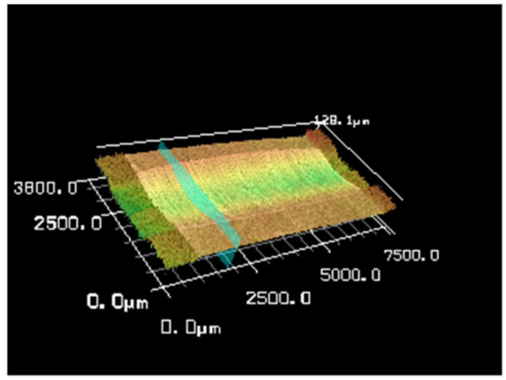


Profile1	Horz. dist.	Hght. diff.	Hght. ave.	Angle	C.S. length	Wear area	R	Comment
All	3803um	0um	78um	0°	4319um	71976um2		
Seg.1	2486um	8um	72um	0°	2716um	62622um2		

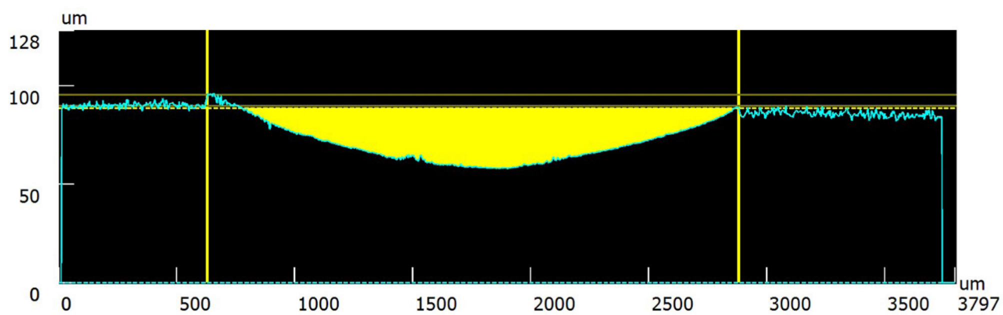
- Wear scars were analyzed using laser scanning confocal microscopy.
- 5 profiles were measured for each sample to obtain an average wear scar width (one profile shown above for this sample).

LSCM Analysis

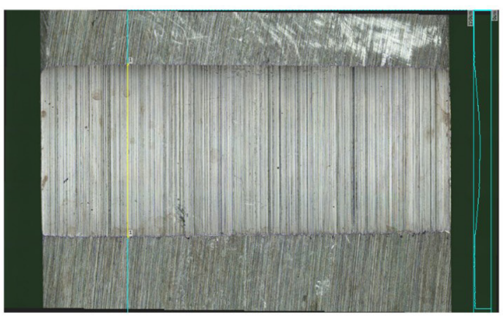
T3 CX105 - Sample 2 and Sample 3

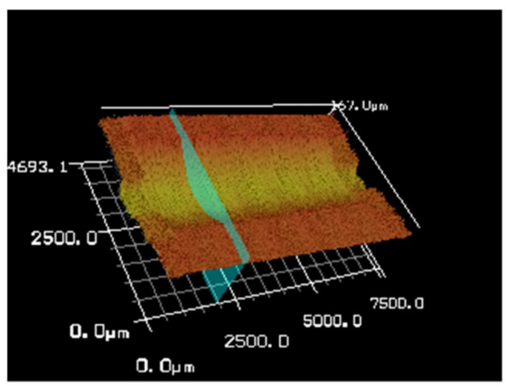


Sample 2

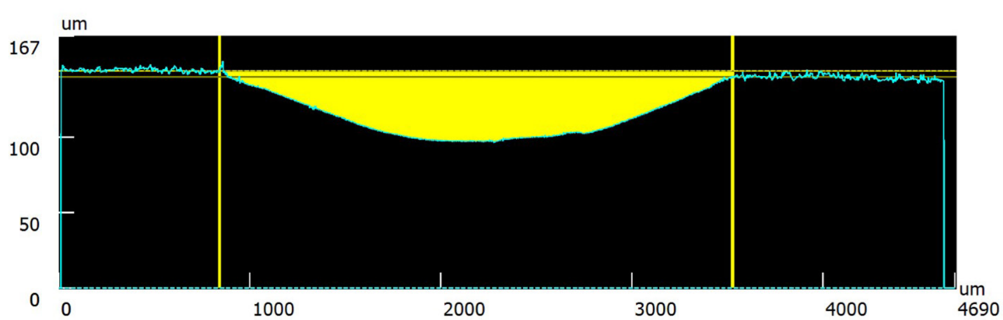


Profile1	Horz. dist.	Hght. diff.	Hght. ave.	Angle	C.S. length	Wear area	R	Comment
All	3797um	0um	76um	0°	4162um	48103um2		
Seg.1	2247um	6um	71um	0°	2283um	39769um2		





Sample 3

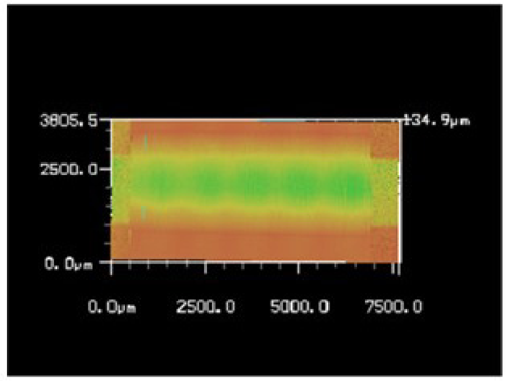


Profile1	Horz. dist.	Hght. diff.	Hght. ave.	Angle	C.S. length	Wear area	R	Comment
All	4690um	0um	123um	0°	5160um	95476um2		
Seg.1	2680um	4um	113um	0°	2718um	81304um2		

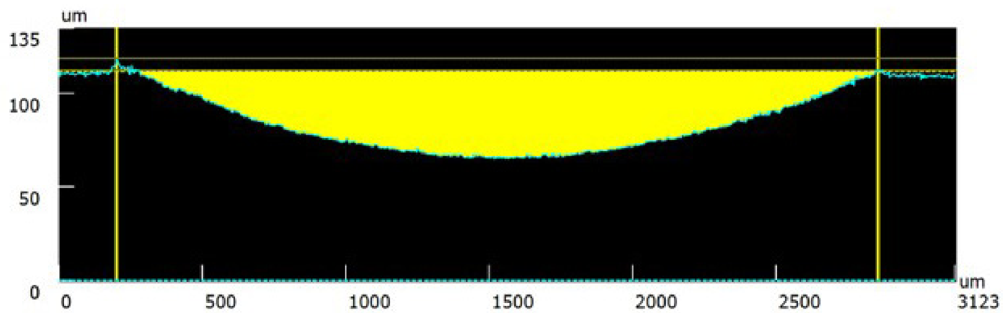
- Wear scars were analyzed using laser scanning confocal microscopy.
- 5 profiles were measured for each sample to obtain an average wear scar width (one profile shown above for these samples).

LSCM Analysis

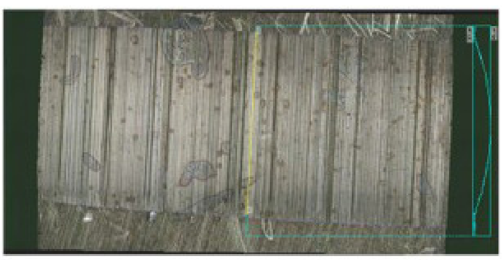
T2 CX90 - Sample 1 and Sample 2

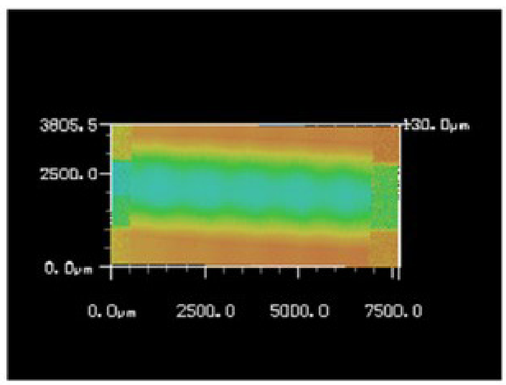


Sample 1

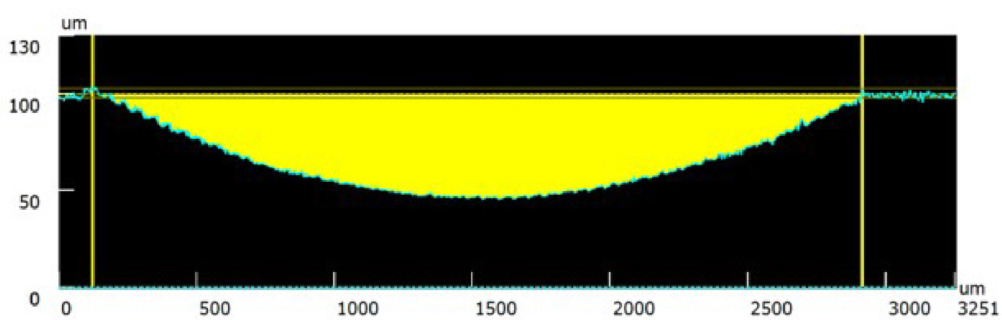


Profile1	Horz. dist.	Hght. diff.	Hght. ave.	Angle	C.S. length	Wear area	R	Comment
All	3123um	2um	86um	0°	3244um	77039um2		
Seg.1	2648um	6um	82um	0°	2738um	76546um2		





Sample 2

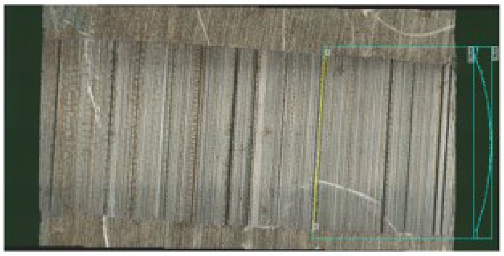


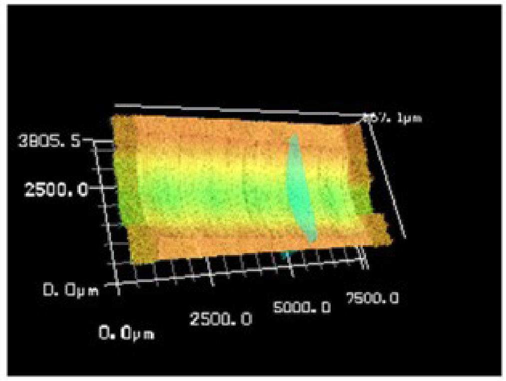
Profile1	Horz. dist.	Hght. diff.	Hght. ave.	Angle	C.S. length	Wear area	R	Comment
All	3251um	3um	69um	0°	3460um	96474um2		
Seg.1	2786um	5um	65um	0°	2948um	96198um2		

- Wear scars were analyzed using laser scanning confocal microscopy.
- 5 profiles were measured for each sample to obtain an average wear scar width (one profile shown above for these samples).

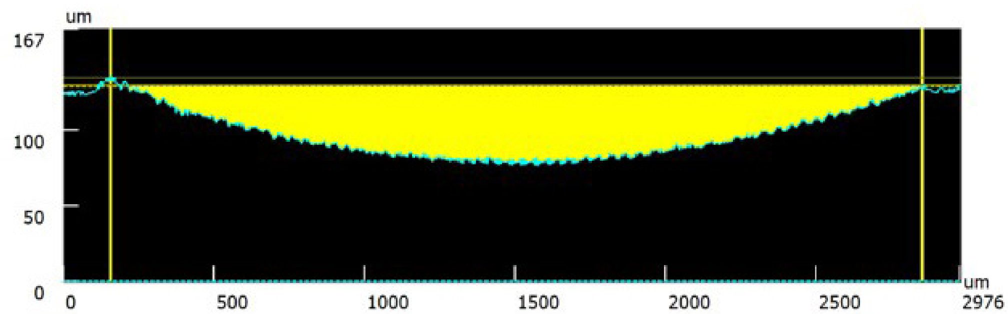
LSCM Analysis

T2 CX90 - Sample 3 and Sample 4

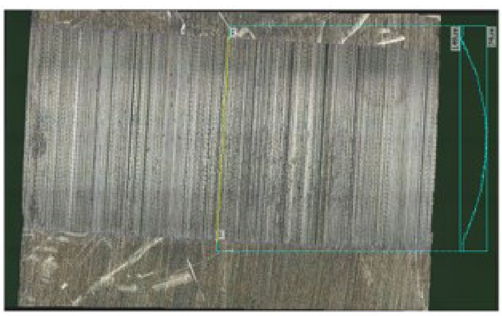


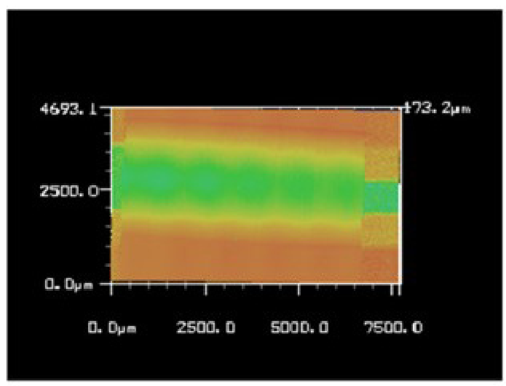


Sample 3

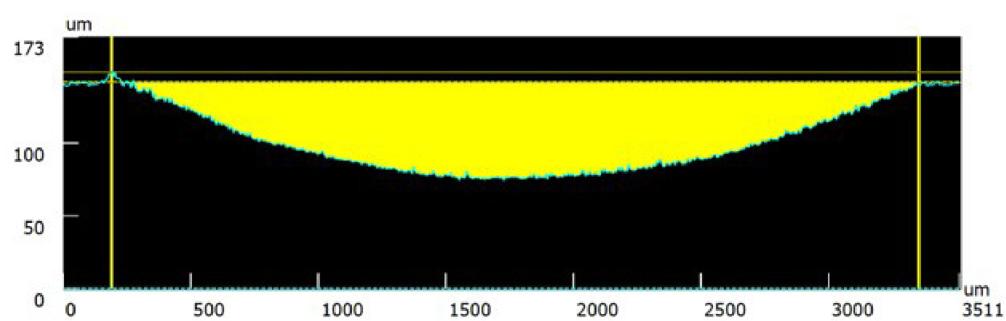


Profile1	Horz. dist.	Hght. diff.	Hght. ave.	Angle	C.S. length	Wear area	R	Comment
All	2976um	1um	99um	0º	3335um	86652um2		
Seg.1	2691um	5um	96um	0º	3009um	86026um2		





Sample 4

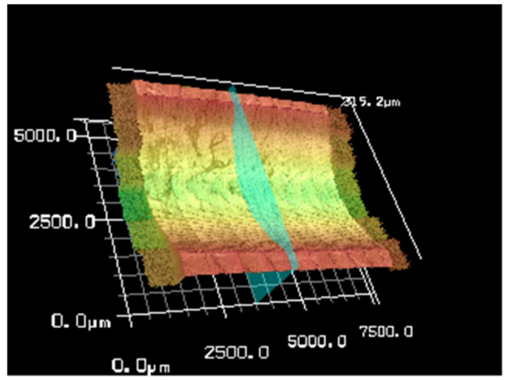


Profile1	Horz. dist.	Hght. diff.	Hght. ave.	Angle	C.S. length	Wear area	R	Comment
All	3511um	0um	103um	0º	3648um	134888um2		
Seg.1	3157um	7um	99um	0º	3284um	134675um2		

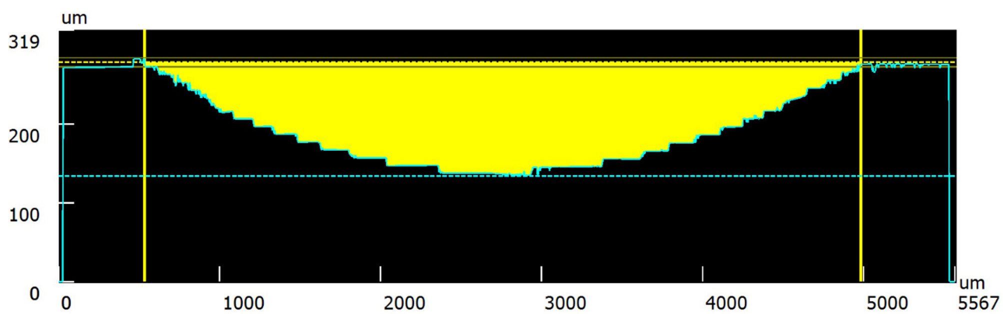
- Wear scars were analyzed using laser scanning confocal microscopy.
- 5 profiles were measured for each sample to obtain an average wear scar width (one profile shown above for these samples).

LSCM Analysis

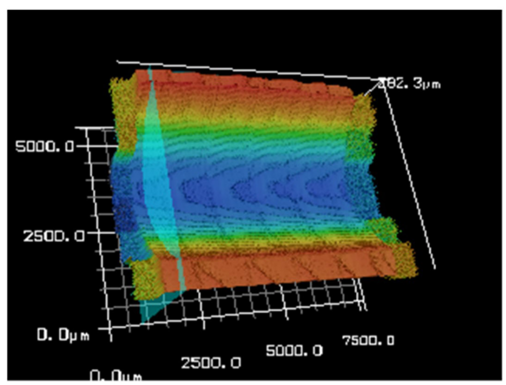
Mn Bronze - Sample 1 and Sample 2



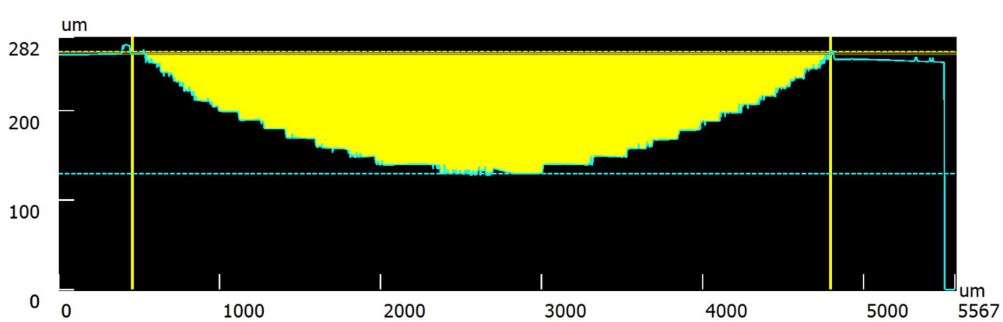
Sample 1



Profile1	Horz. dist.	Hght. diff.	Hght. ave.	Angle	C.S. length	Wear area	R	Comment
All	5567um	0um	199um	0°	6552um	422741um2		
Seg.1	4441um	11um	184um	0°	4822um	410402um2		



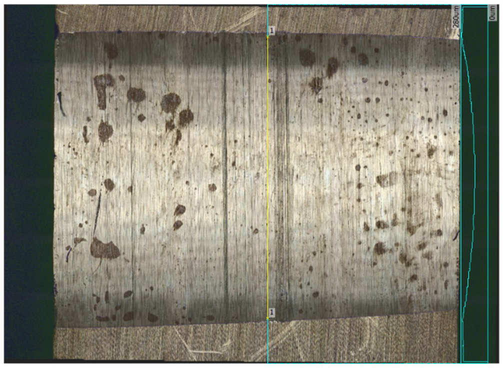
Sample 2

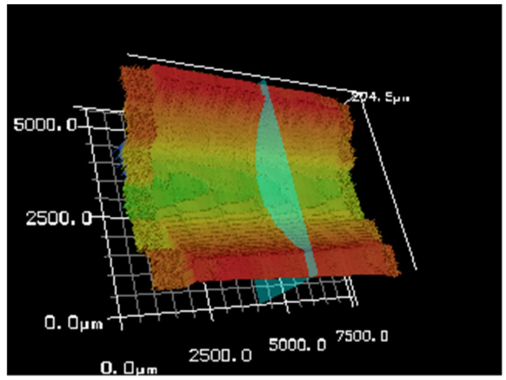


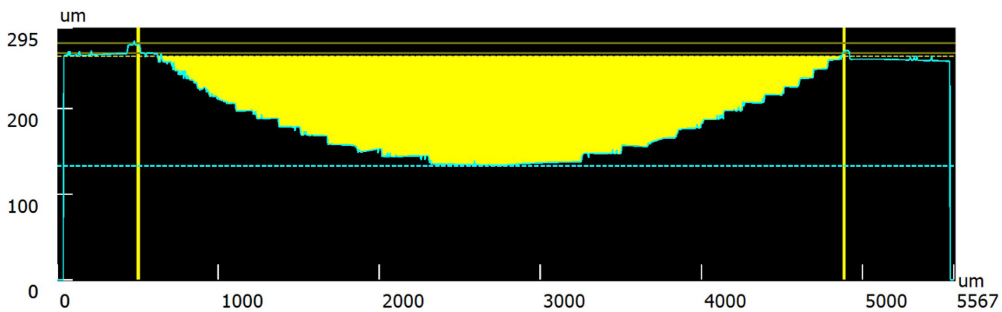
Profile1	Horz. dist.	Hght. diff.	Hght. ave.	Angle	C.S. length	Wear area	R	Comment
All	5567um	262um	191um	3°	6359um	402137um2		
Seg.1	4329um	2um	175um	0°	4827um	386842um2		

- Wear scars were analyzed using laser scanning confocal microscopy.
- 5 profiles were measured for each sample to obtain an average wear scar width (one profile shown above for these samples).

LSCM Analysis
Mn Bronze - Sample 3







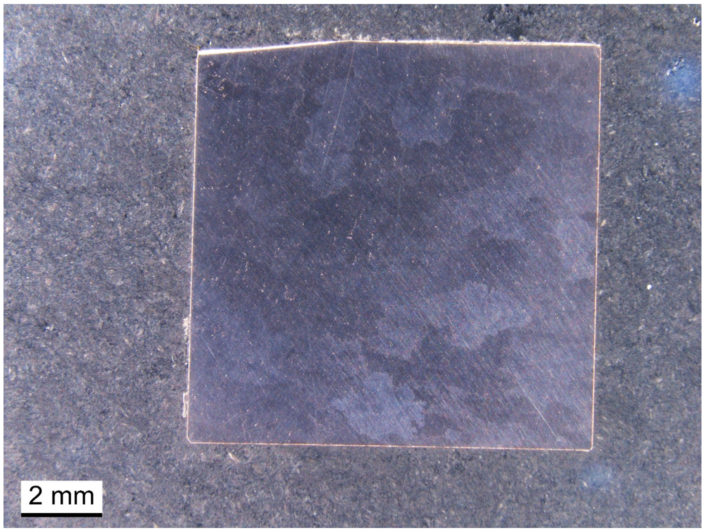
Profile1	Horz. dist.	Hght. diff.	Hght. ave.	Angle	C.S. length	Wear area	R	Comment
All	5567um	0um	193um	0°	6454um	366160um2		
Seg.1	4374um	11um	179um	0°	4698um	356070um2		

- Wear scars were analyzed using laser scanning confocal microscopy.
- 5 profiles were measured for each sample to obtain an average wear scar width (one profile shown above for this sample).

Microstructure Analysis

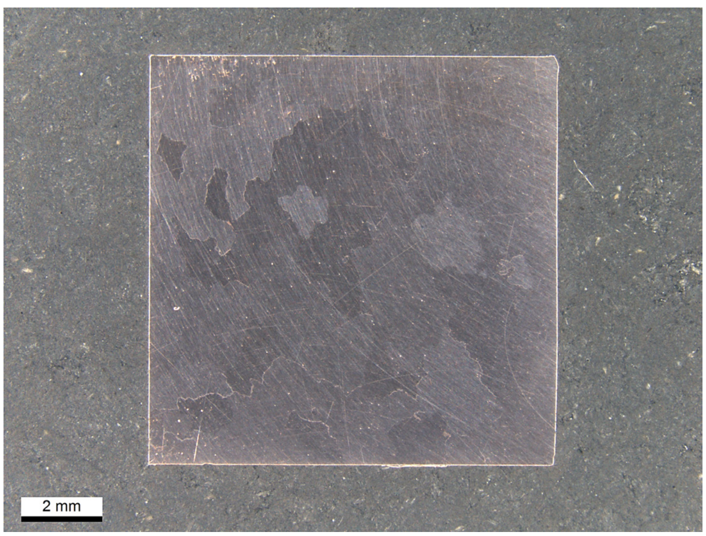
- Macroscopic and microscopic optical metallography was performed to compare the microstructure of the Materion and Mn Bronze alloys.
- Samples were etched prior to imaging using an etchant that comprised 3 g ammonium persulfate, 1 mL NH_4OH, and 100 mL water.

Macroscopic Optical Metallography - T3 CX105



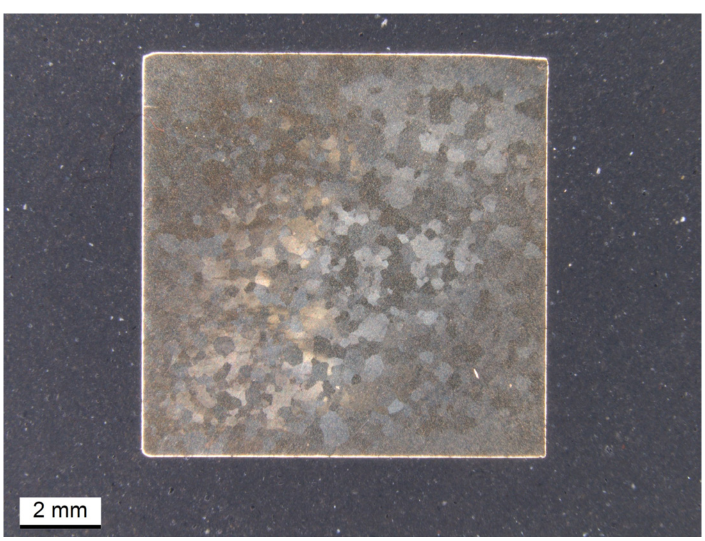
Macroscopic optical metallography shows the T3 CX105 alloy has a relatively large cast grain structure and no signs of large dendrites at this magnification.

Macroscopic Optical Metallography - T2 CX90



Macroscopic optical metallography shows the T2 CX90 alloy has a comparable cast grain size to that of the T3 CX105 alloy with no signs of large dendrites.

Macroscopic Optical Metallography - Mn Bronze Alloy

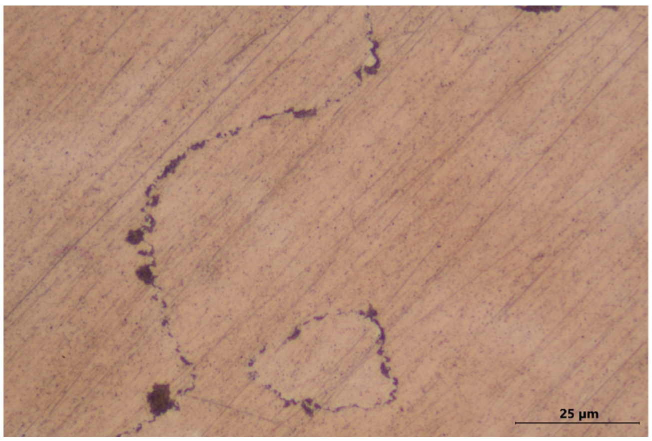


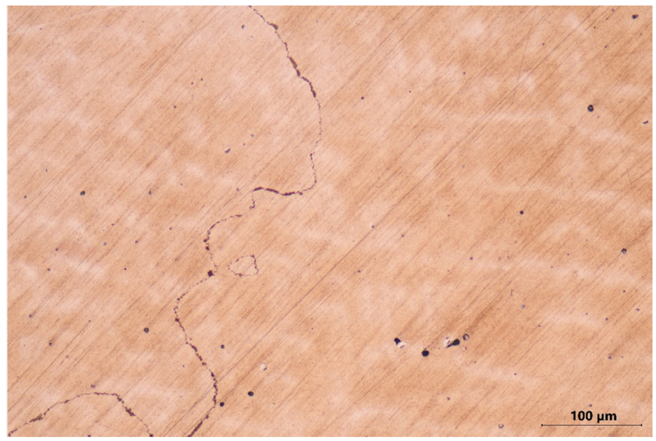
Macroscopic optical metallography shows the Mn Bronze alloy has considerably smaller cast grain size than the Materion alloys. This is due to the addition of Fe, which is a strong grain refiner. Limited dendrites or microsegregation is present due to small temperature window over which solidification occurs in this alloy.

Optical Metallography

T3 CX105 – Location 1

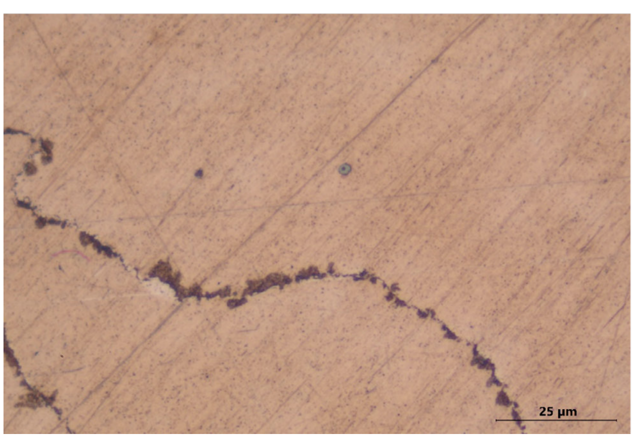
- Location 1 of the T3 CX105 material reveals fine dendritic structure with limited microsegregation. The as-cast grain size again appears large but also appears to be uniform.
- Reduced microsegregation will result in a more uniform composition and improved strength when heat treated.
- Intermetallic particles are found throughout the grain interior and also located along grain boundaries.

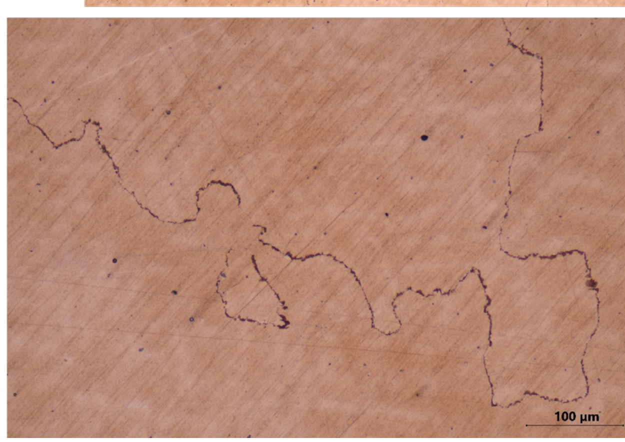




T3 CX105 – Location 2

- Location 2 of the T3 CX105 material once again reveals a fine dedritic structure with limited microsegregation. The as-cast grain size again appears large but uniform.
- Reduced microsegregation will result in a more uniform composition and improved strength when heat treated.
- Intermetallic particles are found throughout the grain interior and also located along grain boundaries.

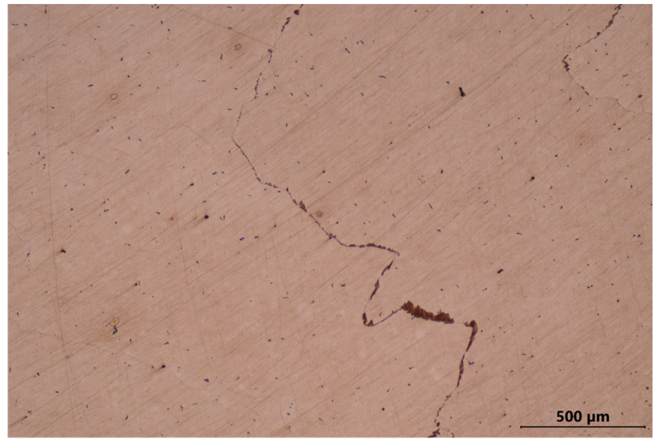


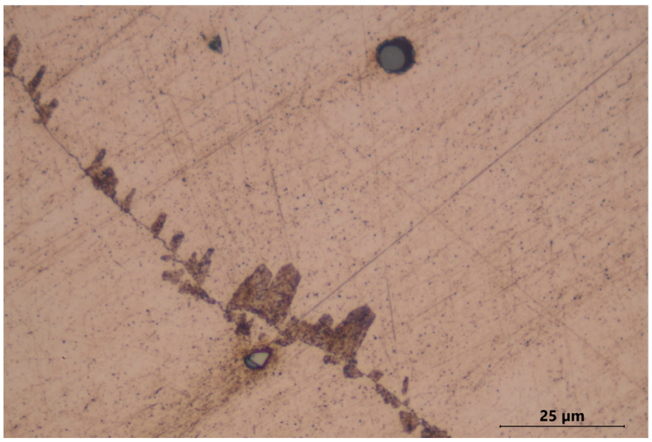


Optical Metallography

T2 CX90 – Location 1

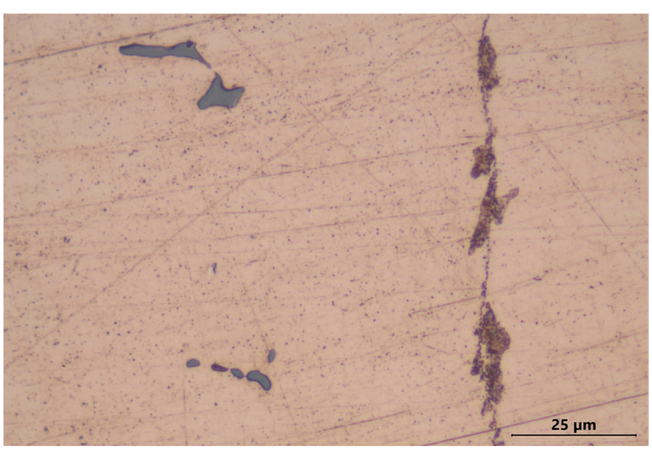
- Location 1 of the T2 CX90 material reveals limited (if any) microsegregation. The as-cast grain size appears large but once again appears uniform.
- Reduced microsegregation will result in a more uniform composition and improved strength following subsequent heat treatment.
- Intermetallic particles are found throughout the grain interior and also located along grain boundaries.

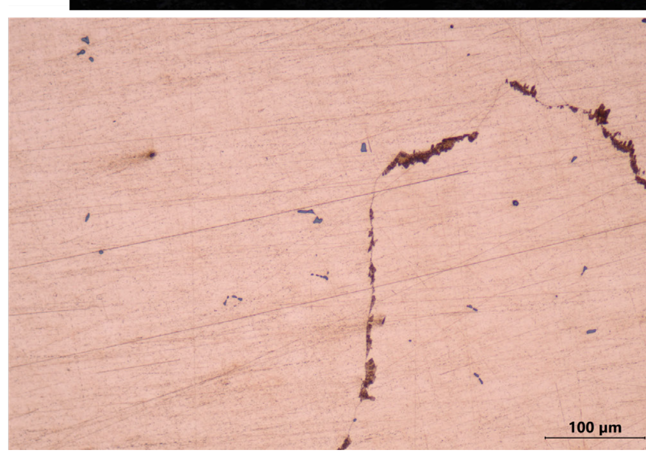




T2 CX90 – Location 2

- Location 2 of the T2 CX90 material reveals limited (if any) microsegregation. The as-cast grain size again appears large but uniform.
- Reduced microsegregation will result in a more uniform composition and improved strength following subsequent heat treatment.
- Intermetallic particles are found throughout the grain interior and also located along grain boundaries.

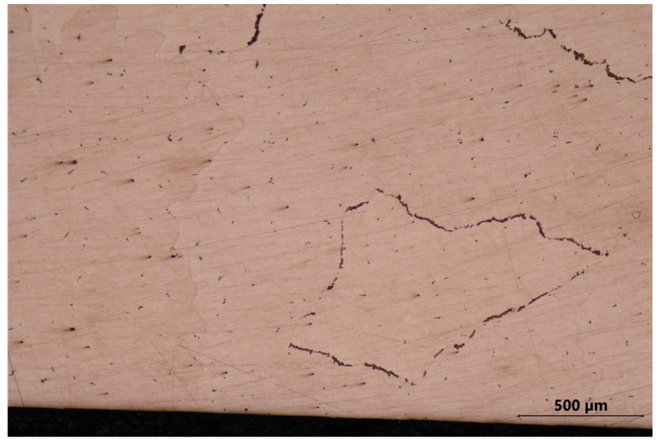


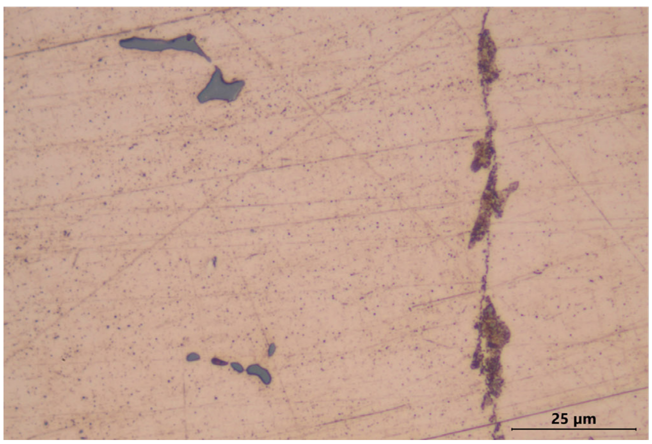


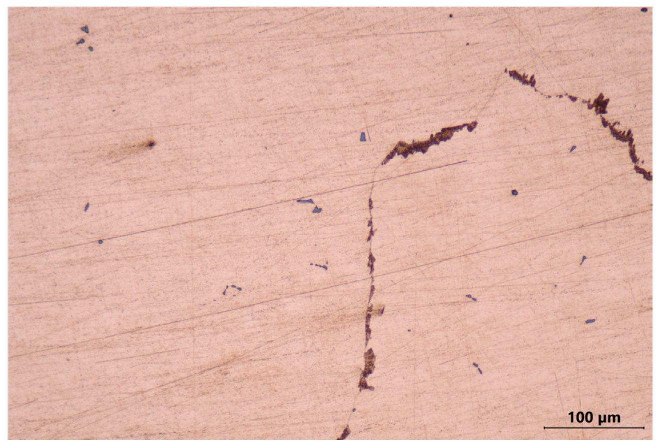
Optical Metallography

T2 CX90 – Location 2

- To confirm the limited microsegregation in T2 CX90 compared to T3 CX105 the specimen was re-polished and retched 4X longer than previous samples.
- These micrographs were obtained from Location 2, identical to that provided on the previous page.
- As can be observed here the specimen still does not show microsegregation.
- This material was heat treated substantially and simply contains reduced alloying element composition.



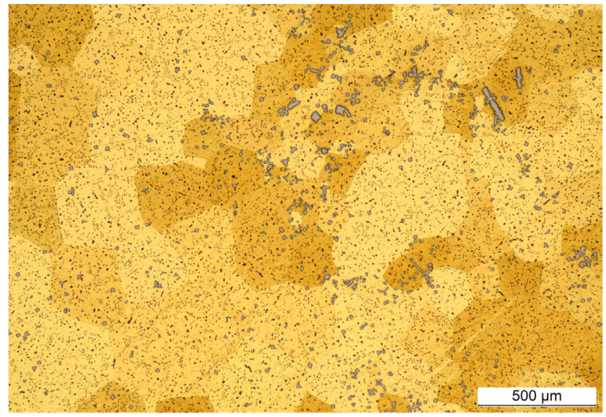


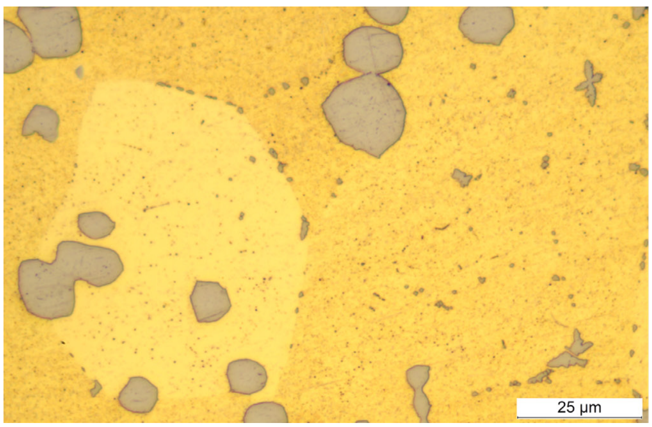


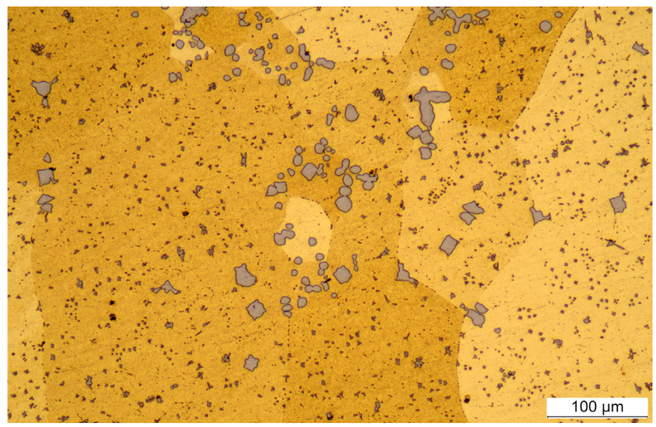
Optical Metallography

Mn Bronze – Location 1

- Location 1 of the Mn Bronze (C86300) material reveals limited (if any) microsegregation. This occurs due to the rapid solidification that occurs during casting of this alloy. The as-cast grain size is small due to the addition of Fe as a grain refiner.
- The microstructure comprises a beta-phase copper matrix with both small and large Fe-Zn (or Fe-Al-Zn) precipitates (gray particles). Beta phase Cu forms in this alloy due to relatively high Zn and more importantly elevated Al content (beta stabilizer). This phase provides high strength and good ductility.
- The microstructure is typical for C86300 alloy.

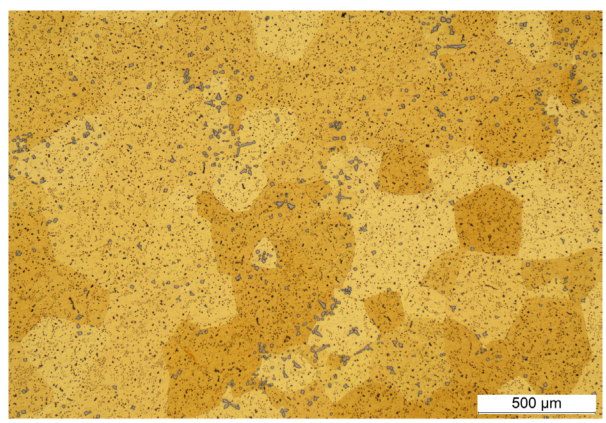


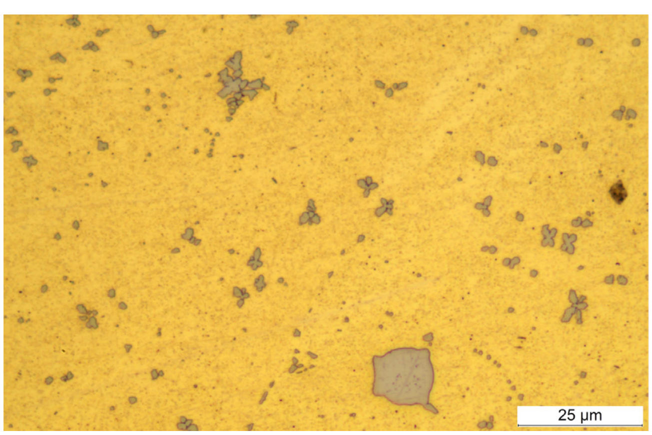


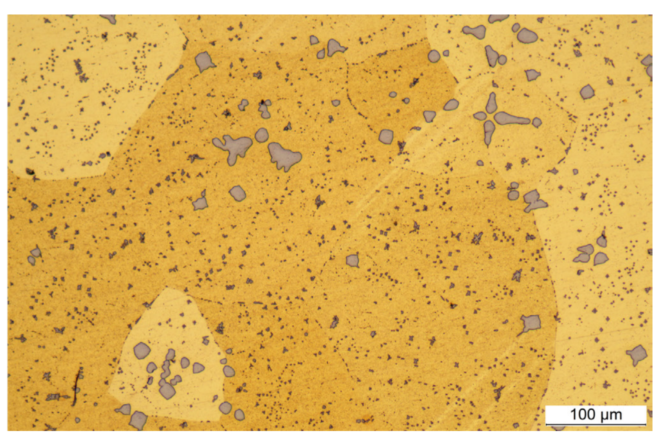


Mn Bronze – Location 2

- Location 2 of the Mn Bronze (C863) material reveals limited (if any) microsegregation.
- The microstructure comprises a beta-phase copper matrix with both small and large Fe-Zn (or Fe-Al-Zn) precipitates (gray particles).
- The microstructure is typical for C86300 alloy.
- Note, C86300 is commonly referred to as manganese bronze but is actually a high strength yellow brass (high Zn content).







Conclusion

Overall, the two Materion alloys (T3 CX105 and T2 CX90) are similar in many respects. The casting procedure, and subsequent heat treatment, used for these alloys results in a highly uniform microstructure with limited microsegregation. Consequently, both alloys exhibit high hardness and good wear resistance. Moreover, the wear behavior, hardness, and microstructure for the T3 CX105 and T2 CX90 alloys are generally very similar, however, a few differences were observed. First, the T2 CX90 alloy (33.6 ± 1.3 HRC) exhibits comparable average hardness but slightly higher hardness variability (largely attributed to a single measurement) compared to the T3 CX105 (34.2 ± 0.7 HRC). Also, the microstructure in the T2 CX90 alloy is very uniform and less microsegregation was observed compared to the T3 CX105 alloy. However, the T2 CX90 alloy exhibits marginally worse wear behavior (in terms of volume loss) but slightly improved CoF. These differences can largely be explained by the reduced alloy content in the T2 CX90 alloy (Cu-9Ni-6Sn) versus the T3 CX105 alloy (Cu-15Ni-8Sn). Consequently, the T3 CX105 alloy is often used in heavily loaded bushings or bearings. Also, the T3 CX105 alloy is expected to exhibit improved tarnish and corrosion resistance compared to T2 CX90. In this study, slightly more tarnishing was observed for the T2 CX90 alloy during sliding wear tests (see wear scar images).

Finally, the Mn Bronze alloy exhibited significantly lower hardness compared to the two Materion alloys. The Mn Bronze also exhibited considerably worse wear resistance under lubricated sliding wear (ASTM G77) compared to the Materion Cu-Ni-Sn alloys. This behavior can be attributed to the much lower mechanical strength (lower hardness) for the Mn Bronze alloy compared to the Cu-Ni-Sn alloys (Materion).