



# Standard Guide for Determining Synergism Between Wear and Corrosion<sup>1</sup>

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## 1. Scope

1.1 This guide covers and provides a means for computing the increased wear loss rate attributed to synergism or interaction that may occur in a system when both wear and corrosion processes coexist. The guide applies to systems in liquid solutions or slurries and does not include processes in a gas/solid system.

1.2 This guide applies to metallic materials and can be used in a generic sense with a number of wear/corrosion tests. It is not restricted to use with approved ASTM test methods.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

## 2. Referenced Documents

2.1 *ASTM Standards:*<sup>2</sup>

**G3** Practice for Conventions Applicable to Electrochemical Measurements in Corrosion Testing

**G5** Reference Test Method for Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements

**G15** Terminology Relating to Corrosion and Corrosion Testing

**G40** Terminology Relating to Wear and Erosion

**G59** Test Method for Conducting Potentiodynamic Polarization Resistance Measurements

**G102** Practice for Calculation of Corrosion Rates and Related Information from Electrochemical Measurements

## 3. Terminology

3.1 *Definitions*—For general definitions relating to corrosion see Terminology **G15**. For definitions relating to wear see Terminology **G40**.

<sup>1</sup> This guide is under the jurisdiction of ASTM Committee **G02** on Wear and Erosion and is the direct responsibility of Subcommittee **G02.40** on Non-Abrasive Wear.

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<sup>2</sup> For referenced ASTM standards, visit the ASTM website, [www.astm.org](http://www.astm.org), or contact ASTM Customer Service at [service@astm.org](mailto:service@astm.org). For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

## 3.2 Definitions of Terms Specific to This Standard:

3.2.1 *cathodic protection current density,  $i_{cp}$* —the electrical current density needed during the wear/corrosion experiment to maintain the specimen at a potential which is one volt cathodic to the open circuit potential.

3.2.2 *corrosion current density,  $i_{cor}$* —the corrosion current density measured by electrochemical techniques, as described in Practice **G102**.

3.2.3 *electrochemical corrosion rate,  $C$* —the electrochemical corrosion rate as determined by Practice **G59** and converted to a penetration rate in accordance with Practice **G102**. This penetration rate is equivalent to the volume loss rate per area. The term  $C_w$  is the electrochemical corrosion rate during the corrosive wear process, and the term  $C_o$  designates the electrochemical corrosion rate when no mechanical wear is allowed to take place.

3.2.4 *mechanical wear rate,  $W_o$* —the rate of material loss from a specimen when the electrochemical corrosion rate has been eliminated by cathodic protection during the wear test.

3.2.5 *total material loss rate,  $T$* —the rate of material loss from a specimen exposed to the specified conditions, including contributions from mechanical wear, corrosion, and interactions between these two.

3.2.6 *wear/corrosion interaction*—the change in material wastage resulting from the interaction between wear and corrosion, that is,  $T$  minus  $W_o$  and  $C_o$ . This can be sub-divided into  $\Delta C_w$ , the change of the electrochemical corrosion rate due to wear and  $\Delta W_c$ , the change in mechanical wear due to corrosion.

## 4. Summary of Guide

4.1 A wear test is carried out under the test conditions of interest and  $T$  is measured.

4.2 Additional experiments are conducted to isolate the mechanical and corrosion components of the corrosive wear process. These are as follows:

4.2.1 A repeat of the experiment in **4.1** with measurement of  $C_w$ ,

4.2.2 A test identical to the initial experiment in **4.1**, except that cathodic protection is used to obtain  $W_o$ , and

4.2.3 Measurement of  $C_o$ , the corrosion rate in the absence of mechanical wear.

4.3  $\Delta C_w$  and  $\Delta W_c$  are calculated from the values measured in the experiments described in 4.1 and 4.2.

## 5. Significance and Use

5.1 Wear and corrosion can involve a number of mechanical and chemical processes. The combined action of these processes can result in significant mutual interaction beyond the individual contributions of mechanical wear and corrosion (1-5).<sup>3</sup> This interaction among abrasion, rubbing, impact and corrosion can significantly increase total material losses in aqueous environments, thus producing a synergistic effect. Reduction of either the corrosion or the wear component of material loss may significantly reduce the total material loss. A practical example may be a stainless steel that has excellent corrosion resistance in the absence of mechanical abrasion, but readily wears and corrodes when abrasive particles remove its corrosion-resistant passive film. Quantification of wear/corrosion synergism can help guide the user to the best means of lowering overall material loss. The procedures outlined in this guide cannot be used for systems in which any corrosion products such as oxides are left on the surface after a test, resulting in a possible weight gain.

## 6. Procedures

6.1 A wear test where corrosion is a possible factor is performed after the specimen has been cleaned and prepared to remove foreign matter from its surface. Volume loss rates per unit area are then calculated, and the results tabulated. The value of  $T$  is obtained from these measurements. Examples of wear tests involving corrosion are detailed in papers contained in the list of references. These examples include a slurry wear test (1-3), a slurry jet impingement test (6), and a rotating cylinder-anvil apparatus (7).

6.2 A wear test described in 6.1 is repeated, except that the wear specimen is used as a working electrode in a typical 3 electrode system. The other two electrodes are a standard reference electrode and a counter electrode as described in Practices G3 and G59, and Reference Test Method G5. This test is for electrochemical measurements only, and no mass or volume losses are measured because they could be affected by the electrical current that is passed through the specimen of interest during the experiments. Two measurements are made, one to measure the polarization resistance as in Practice G59, and one to generate a potentiodynamic polarization curve as in Test Method G5. The open circuit corrosion potential,  $E_{cor}$ , the polarization resistance,  $R_p$ , and Tafel constants,  $\beta_a$  and  $\beta_c$ , are tabulated. The exception to Test Method G5 is that the apparatus, cell geometry, and solutions or slurries used are defined by the particular wear test being conducted, and are not restricted to the electrochemical cell or electrolyte described in Test Method G5. The potentiodynamic method rather than the potentiostatic method is recommended.  $R_p$ ,  $\beta_a$ , and  $\beta_c$  are used to calculate the electrochemical corrosion current density,  $i_{cor}$  as described in Practice G59. The value for  $i_{cor}$  is then

converted to a penetration rate in accordance to Practice G102. This penetration rate is equivalent to the material loss rate,  $C_w$ .

6.3 A wear test similar to that conducted in 6.2 is run again except that the wear specimen is polarized one volt cathodic with respect to  $E_{cor}$  so that no corrosion takes place. The mass loss of the specimen is measured during the cathodic protection period by weighing it before and after the test.  $W_o$  is then calculated by dividing the mass loss by the specimen density and exposed surface area. The current density  $i_{cp}$  is also recorded. Caution must be used when using this technique because some metals or alloys may be affected by hydrogen embrittlement as a result of hydrogen that may be generated during this test. If hydrogen evolution is too great, then there is always a possibility that the hydrodynamics of the system could be affected. However, the results of research (1-7) have shown these effects to be minimal for the ferrous alloys studied to date.

6.4 A corrosion test similar to that conducted in 6.2 is run again except no mechanical wear is allowed to act on the specimen surface. The penetration rate, which is equivalent to  $C_o$ , is obtained as in 6.2, using polarization resistance and potentiodynamic polarization scans to obtain  $R_p$ ,  $\beta_a$ ,  $\beta_b$ , and  $i_{cor}$ .

6.5  $T$ ,  $W_o$ ,  $C$ ,  $C_w$  and  $C_o$  are all reported in units of volume loss per exposed area per unit time. The synergism between wear and corrosion is calculated according to (Eq 1), (Eq 2), and (Eq 3).

6.6 Caution must be used to make sure that the surface area exposed to corrosion is the same as that exposed to mechanical wear. Coating of the portions of the specimen with a non-conductor to mask off areas to prevent corrosion is an effective means of doing this.

## 7. Calculation of Wear/Corrosion Interaction

7.1 The total material loss,  $T$ , is related to the synergistic component,  $S$ , that part of the total damage that results from the interaction of corrosion and wear processes, by the following equation

$$T = W_o + C_o + S \quad (1)$$

7.2 The total material loss,  $T$ , can be divided into the following components, the wear rate in the absence of corrosion, the corrosion rate in the absence of wear, and the sum of the interactions between the processes:

$$T = W_o + C_o + \Delta C_w + \Delta W_c \quad (2)$$

where  $\Delta C_w$  is the change in corrosion rate due to wear and  $\Delta W_c$  is the change in wear rate due to corrosion.

$$W_c = W_o + \Delta W_c \quad (3)$$

where  $W_c$  is the total wear component of  $T$ .

$$C_w = C_o + \Delta C_w \quad (4)$$

where  $C_w$  is the total corrosion component of  $T$  and can be measured by electrochemical means.

7.3 The term “synergistic effect” is now usually used to refer to the enhancement of wear due to corrosion  $\Delta W_c$ . Negative synergism (or antagonism) occurs when the corrosion product during wear provides better protection than the initial surface; an example would be the formation of adherent oxide

<sup>3</sup> The boldface numbers in parentheses refer to the list of references at the end of this standard.

TEST	—Test Number:						
DATE	—Date:						
ENVIRONMENT	—Description:						
SPECIMEN Identification:	Material property		Wear Specimen		Counterface Material		
	Density, g/cm <sup>3</sup>						
	Specimen area, mm <sup>2</sup>						
	Equivalent weight						
WEAR TESTS	Initial wt, g	Final wt, g	Wt loss, g	Time, h	Material loss, mm <sup>3</sup> / mm <sup>2</sup>	Material loss rate, mm <sup>3</sup> / mm <sup>2</sup> -yr	Material loss rate symbol
Corrosive Wear Test							<i>T</i>
Cathodic Protection Test							<i>W<sub>0</sub></i>
ELECTRO- CHEMICAL TESTS	<i>E<sub>cor</sub></i> , mV vs SCE	<i>i<sub>cor</sub></i> , μA/cm <sup>2</sup>	<i>R<sub>p</sub></i> , ohms-cm <sup>2</sup>	<i>β<sub>a</sub></i> , mV/ decade	<i>β<sub>c</sub></i> , mV/ decade	Material loss rate, mm <sup>3</sup> / mm <sup>2</sup> -yr	Material loss rate symbol
Electrochemical test with wear							<i>C<sub>w</sub></i>
Electrochemical test without wear							<i>C<sub>0</sub></i>

**FIG. 1 Test Data Recording Form**

scale during sliding wear. The term “additive effect” refers to the change in corrosion rate due to wear,  $\Delta C_w$ . In the latter case, the electrochemical corrosion rate, can be added to the wear rate in the absence of corrosion,  $W_0$ , to generate the overall weight change.

From the above, the following dimensionless factors can be defined to describe the degree of synergism:

$T/(T - S)$	(“Total Synergism Factor”)	(i)
$(C_0 + \Delta C_w)/C_0$	(“Corrosion Augmentation Factor”)	(ii)
$(W_0 + \Delta W_c)/W_0$	(“Wear Augmentation Factor”)	(iii)

**7.4 Construction of Wear-Corrosion Map**—A wear-corrosion map is a useful method of identifying wastage regimes and mechanisms (5, 8, 9). The following is a method which enables a wear-corrosion map to be constructed.

7.4.1 Generate at least six test results involving the same variables identifying the components of the interaction given in Section 7, that is, results at six velocities.

7.4.2 For each of these results, generate an additional six tests (identifying the components of the interaction given in Section 7) on the effects of another variable, that is, particle size or pH.

7.4.3 Identify criteria for transitions between tribo-corrosion regimes:

$$T < X \quad \text{Low} \quad (5)$$

$$X \leq T < X1 \quad \text{Medium} \quad (6)$$

$$T \geq X2 \quad \text{High} \quad (7)$$

7.4.4 The limits in 7.4.3 should be based on tolerances identified for the wear-corrosion process. The *Low* region is identified as the safe operating wear-corrosion regime. The various regimes should be labeled on the map.

7.4.5 The map can also be used to identify the extent of the wear and corrosion augmentation factors by defining criteria for the transitions (8, 9) between regimes.

$$\Delta C_w / \Delta W_c < 0.1 \quad (8)$$

Synergistic effects dominate. Corrosion is affecting wear to a great extent than wear is affecting corrosion.

$$0.1 \leq \Delta C_w / \Delta W_c < 1 \quad (9)$$

The “additive” and “synergistic” interactions are equal.

$$\Delta C_w / \Delta W_c \geq 1 \quad (10)$$

Additive effects dominate. Wear is affecting corrosion to a greater extent than corrosion is affecting wear.

7.4.6 As in 7.4.4, the various regimes should be highlighted on the map.

7.4.7 If the synergistic effects are negative in Eq 8-10, that is, antagonistic, use the same inequalities but take the modulus of  $\Delta W_c$  in the evaluation of  $\Delta C_w / \Delta W_c$  in the determination of the regime boundaries).

## 8. Report <sup>4</sup>

8.1 The report should include the test method used and the test conditions.

8.2 A sample of a Test Data Recording form is shown in Fig. 1.

8.3 A sample of a Test Summary form for several tests is shown in Fig. 2.

## 9. Keywords

9.1 aqueous; corrosion; electrochemical; erosion-corrosion; slurries; solutions; synergism; wear

<sup>4</sup> See appendixes for examples of parameter calculations and test data.

TEST	SPECIMEN	COUNTERFACE MATERIAL	Material loss rate, $\frac{\text{mm}^3}{\text{mm}^2\text{-yr}}$						Unitless factors		
			$T$	$W_o$	$C_o$	$C_w$	$S$	$\Delta C_w$	$\Delta W_c$	Corrosion augmentation	Wear augmentation

**FIG. 2 Test Summary Form**

## APPENDIXES

### (Nonmandatory Information)

#### X1. SAMPLES OF TEST DATA

TEST	—Test Number:											
DATE	—Date:											
ENVIRONMENT	—Description:											
SPECIMEN Identification: A514 steel	Material property				Wear Specimen			Counterface Material				
	—Density, $\text{g/cm}^3$				$7.83 \times 10^{-3}$			2 wt pct silica sand (50 × 70 mesh) in water slurry @25°C				
	—Specimen area, $\text{mm}^2$				654							
	—Equivalent weight				27.92							
WEAR TESTS	Initial wt, g	Final wt, g	Wt loss, g	Time, h	Material loss, $\frac{\text{mm}^3}{\text{mm}^2}$	Material loss rate, $\frac{\text{mm}^3}{\text{mm}^2\text{-yr}}$	Material loss rate symbol					
	Corrosive Wear Test	56.3057	56.0793	0.2264	1.00	0.044	387	$T$				
	Cathodic Protection Test	56.0495	55.9035	0.1460	1.00	0.029	249	$W_o$				
ELECTROCHEMICAL TESTS	$E_{cor}$ , mV vs SCE	$i_{cor}$ , $\mu\text{A/cm}^2$	$R_p$ , ohms-cm <sup>2</sup>	$\beta_a$ , $\frac{\text{mV}^3}{\text{decade}}$	$\beta_c$ , $\frac{\text{mV}^3}{\text{decade}}$	Material loss rate, $\frac{\text{mm}^3}{\text{mm}^2\text{-yr}}$	Material loss rate symbol					
	Electrochemical test with wear	-519	322	80.4	95	160	3.75	$C_w$				
	Electrochemical test without wear	-420	180	102	90	80	2.10	$C_o$				

#### X2. SAMPLE OF TEST SUMMARY

TEST	SPECIMEN	COUNTERFACE MATERIAL	Material loss rate, $\frac{\text{mm}^3}{\text{mm}^2\text{-yr}}$						Unitless factors		
			$T$	$W_o$	$C_o$	$C_w$	$S$	$\Delta C_w$	$\Delta W_c$	Corrosion augmentation	Wear augmentation
1	A514 steel	2 wt pct silica sand (50 × 70) in water slurry @ 25°C	387	249	2.10	3.75	136	134	1.65	1.79	1.54
2	316 SS	2 wt pct silica sand (50 × 70) in water slurry @ 25°C	427	272	0.465	9.95	154	145	9.49	21.4	1.53
3	REM 500	2 wt pct silica sand (50 × 70) in water slurry @ 25°C	222	168	0.990	1.27	53.0	52.7	0.3	1.28	1.31

#### X3. SAMPLE CALCULATION FOR TOTAL MATERIAL LOSS RATE

##### X3.1 Data

- X3.1.1 Corrosive Wear Test duration—1 h.
- X3.1.2 Specimen Density— $7.84 \text{ g/cm}^3$ .
- X3.1.3 Specimen Area— $654 \text{ mm}^2$ .
- X3.1.4 Initial mass of sample— $56.3057 \text{ g}$ .
- X3.1.5 Final mass of sample— $56.0793 \text{ g}$ .

##### X3.2 Calculation

$$T = \left[ \frac{56.3057 \text{ g} - 56.0793 \text{ g}}{654 \text{ mm}^2 \times 7.84 \times 10^{-3} \frac{\text{g}}{\text{mm}^3} \times 1 \text{ h}} \right] \times 24 \frac{\text{h}}{\text{d}}$$

$$\times 365 \frac{\text{d}}{\text{yr}} = 387 \frac{\text{mm}^3}{\text{mm}^2\text{-yr}} \quad (\text{X3.1})$$

**X4. SAMPLE CALCULATION FOR MECHANICAL WEAR RATE**
**X4.1 Data**

- X4.1.1 Mechanical Wear Rate in mm<sup>2</sup>/mm<sup>2</sup>-yr.
- X4.1.2 Cathodic Protection Test duration—1 h.
- X4.1.3 Specimen Density—7.84 g/cm<sup>3</sup>.
- X4.1.4 Specimen Area—654 mm<sup>2</sup>.
- X4.1.5 Initial mass of sample—56.0495 g.
- X4.1.6 Final mass of sample—55.9035 g.

**X4.2 Calculation**

$$W_0 = \left[ \frac{56.0495 \text{ g} - 55.9035 \text{ g}}{654 \text{ mm}^2 \times 7.84 \times 10^{-3} \frac{\text{g}}{\text{mm}^3} \times 1 \text{ h}} \right] \times 24 \frac{\text{h}}{\text{d}} \times 365 \frac{\text{d}}{\text{yr}}$$

$$= 249 \frac{\text{mm}^3}{\text{mm}^2\text{-yr}} \quad (\text{X4.1})$$

**X5. SAMPLE CALCULATION FOR ELECTROCHEMICAL CORROSION RATES**

X5.1 *Data and Requirements*—See **Appendix X1**.

- X5.1.1 Corrosion Rate in mm<sup>3</sup>/mm<sup>2</sup>-yr.
- X5.1.2 Exposed Surface Area = 654 mm<sup>2</sup>.
- X5.1.3  $i_{cor}$  for test with wear—322 μA/cm<sup>2</sup>.
- X5.1.4  $i_{cor}$  for test without wear—180 μA/cm<sup>2</sup>.
- X5.1.5 Specimen Equivalent Weight—27.92 (See **Appendix X2** in Practice **G102** for sample calculation).

$$C_0 = \frac{3.27 \times 10^{-3} \frac{\text{mm-g}}{\mu\text{A-cm-yr}} \times 180 \frac{\mu\text{A}}{\text{cm}^2} \times 27.92}{7.84 \frac{\text{g}}{\text{cm}^3}}$$

$$= 2.10 \frac{\text{mm}}{\text{yr}} = 2.10 \frac{\text{mm}^3}{\text{mm}^2\text{-yr}} \quad (\text{X5.2})$$

X5.2 *Calculations*—See Practice **G102**, **Appendix X3** for calculation of penetration rate.

$$C_w = \frac{3.27 \times 10^{-3} \frac{\text{mm-g}}{\mu\text{A-cm-yr}} \times 322 \frac{\mu\text{A}}{\text{cm}^2} \times 27.92}{7.84 \frac{\text{g}}{\text{cm}^3}}$$

$$= 3.75 \frac{\text{mm}}{\text{yr}} = 3.75 \frac{\text{mm}^3}{\text{mm}^2\text{-yr}} \quad (\text{X5.1})$$

**X6. SAMPLE CALCULATION FOR AMOUNT OF SYNERGISM**

X6.1 *Data and requirements*—See **Appendix X3**, **Appendix X4**, and **Appendix X5**.

X6.2 Calculation in accordance with (Eq 1).

$$S = T - W_0 - C_0 = 387 - 249 - 2.1 = 135.9 \frac{\text{mm}^3}{\text{mm}^2\text{-yr}} \quad (\text{X6.1})$$

X6.3 Calculation in accordance with (Eq 2).

$$\Delta W_c = T - W_0 - C_w = 387 - 249 - 3.75 = 134.25 \frac{\text{mm}^3}{\text{mm}^2\text{-yr}} \quad (\text{X6.2})$$

X6.4 Calculation in accordance with (Eq 3).

$$\Delta C_w = C_w - C_0 = 375 - 210 = 1.65 \frac{\text{mm}^3}{\text{mm}^2\text{-yr}} \quad (\text{X6.3})$$

**X7. SAMPLE CALCULATION FOR CORROSION AND WEAR AUGMENTATION**

X7.1 *Data and requirements*—See **Appendix X3**, **Appendix X4**, **Appendix X5**, and **Appendix X6**.

X7.2 Calculate in accordance with Eq (X7.1).

$$\text{Corrosion Augmentation Factor} = C_w/C_0 = 3.75/2.10 = 1.79 \quad (\text{X7.1})$$

X7.3 Calculate in accordance with Eq (X7.2).

$$\text{Wear Augmentation Factor} = (W_c)/W_0 = (279 + 134)/249 = 1.54 \quad (\text{X7.2})$$

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