NRL Report 6209

Protective Coatings for Magnesium Alloys

Part 1
Effect on Mechanical Properties of a New Technique for Fusing Teflon to Magnesium and Aluminum Alloys

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ABSTRACT

Changes in the tensile and tensile yield strengths after fusing Teflon on magnesium alloy AZ31B-H24, and aluminum alloys 2024-T3, 5052-H32, and 6061-T6 have been studied. The new technique, a flame technique, for fusing Teflon caused less alteration of the mechanical properties than the frequently used 750°F oven method; aluminum alloy 2024-T3 was affected less than the other alloys. The flame or concentrated source of heat is superior to the oven method of heating because the high temperatures used are such that a rapid fusion of the coating can be accomplished without heating the bulk metal to the fusion or decomposition temperature of the coating. The new technique appears applicable to other coatings and substrates, although the thermal conductivities and heat capacities of the substrate and coating must be considered when optimum flame-fusion conditions are sought.

PROBLEM STATUS

This is an interim report; work on the problem is continuing.

AUTHORIZATION

NRL Problem C04-04
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PROTECTIVE COATINGS FOR MAGNESIUM ALLOYS

PART 1 - EFFECT ON MECHANICAL PROPERTIES OF A NEW TECHNIQUE FOR FUSING TEFLON TO MAGNESIUM AND ALUMINUM ALLOYS

INTRODUCTION

The magnesium and aluminum alloys used in aircraft construction are treated with various protective coatings to prevent marine atmosphere corrosion. In addition, aircraft based or being shipped aboard naval vessels are treated according to prescribed procedures to maintain the efficiency of the protective coating. Even with these precautions, extreme corrosion has rendered aircraft unsafe after relatively short marine atmosphere exposures. Improved maintenance procedures and new protective coatings have evolved over the years, but better protective systems are needed. Greatly improved coatings could extend the use of the light metal alloys, especially the more reactive magnesium alloys, and reduce the amount of time required to maintain aircraft in proper operational condition.

The general methods used in the application of protective coatings to metal surfaces can be classified as follows:

1. Chemical reaction between the applied coating and the metal surface. Such reactions may occur under the influence of an electric current, as in anodizing.

2. Solvent evaporation.

3. Solvent evaporation followed by thermal fusion or by thermal or other means of curing.

4. The coating, without a solvent, is sprayed onto a hot metal surface where fusion takes place or the fused coating is sprayed directly onto the heated metal surface.

A disadvantage of the thermal methods with most alloys is the alteration of the mechanical properties. Many promising protective coatings have been rejected because they require thermal cure. DeVries (1) has reported that Kel-F is the best coating on magnesium alloys for resistance to bending, scratching, and the action of distilled water. He noted, however, that this coating was not practical for many magnesium alloys because it requires baking at nearly 500°F, a procedure that could affect the mechanical properties.

This Laboratory has begun the development of improved magnesium protection systems. The study involves three approaches: the chemistry of magnesium and magnesium coordination compounds, magnesium protective systems, and techniques for application or curing protective coatings. Based on information from magnesium chemistry, formulations will be chosen to be tested in other approaches. Concurrently with the study of magnesium coordination chemistry, the application of coatings on alloys by thermal methods was investigated. Since oxides and water between the metal and coating can reduce the effectiveness of protective coatings, a thermal method and properly chosen coating could be used to remove the interfering substances by chemical reaction or evaporation. Where practical, aluminum alloys, extensively used in aircraft construction, were included in this investigation. Commercially available coatings were considered to provide information related to the problems associated with thermal treatments. Teflon was selected for our initial studies.

Where a low coefficient of friction is desired, Teflon coatings have found considerable commercial value on aluminum alloys as well as steel (2). The use of Teflon as a protective coating has been discussed by FitzSimmons and Zisman (3), and more extensively by Thompson and Scott (4) who studied 68 fluorocarbon-primer-enamel systems on aluminum alloys and steel. Even though pores have been noted in the coating surface, the metals are reported to be protected against corrosion. A fluorocarbon-primer surface covered with a fluorocarbon enamel afforded the optimum corrosion protection of steel and aluminum alloys (4). Similar studies of Teflon on magnesium alloys have not yet been reported.

The procedure for applying Teflon coatings to aluminum alloys and steel is given in detail by Thompson and Scott (4-6), FitzSimmons and Zisman (3), and in NAVWEPS OD 23684 (7). The coating is applied by spraying; generally it is fused at an oven temperature of 700° to 725°F to obtain a metal/coating interface temperature of 700°F. Though higher temperatures may be detrimental to the as-received mechanical properties of the metal, a 750°F temperature is frequently used. The heating period varies with the thickness of the metal, and a minimum time of 10 minutes is recommended for thicknesses up to 1/4 inch. Any means of heat for initiating fusion can be used provided they raise the temperature of the Teflon/metal interface to between 700° and 725°F, maintain it there just long enough to fuse the Teflon and not cause local overheating (5,6).

The effects of an oven heat treatment on the mechanical properties of the aluminum alloys 3003, 5154, and 5056 with various tempers have been reported by Thompson and Scott (4). They found that the tensile strength of the annealed aluminum alloys coated with Teflon were "insignificantly" changed by 5 to 10 minute exposures at oven temperatures of 700° to 715°F. The mechanical properties of the hardened alloys were altered so as to approach the annealed condition. They concluded that all other hardened aluminum alloys would undergo a similar change. From this discussion a question arises: Can a technique applicable to both hardened aluminum alloys and magnesium alloys be developed with minimal alteration of the mechanical properties?

The present study was undertaken to determine the effects on the tensile and tensile yield properties after fusion of Teflon on several aluminum and magnesium alloys. Two methods of fusion were employed: the 750°F oven heating and a flame technique that was originally used for a rubber and Teflon system (8).

MATERIALS, APPARATUS, AND PROCEDURE

The magnesium alloys used in this work were AZ31B-H24 and AZ31B-H24, chrome pickle. The aluminum alloys were 2024-T3, 2024-T3 (alclad), 5052-H32, and 6061-T6.

The high tensile strength 2024-T3 alloy was selected because the alloy has been solution heat treated, naturally aged, and cold worked. The clad and unclad alloys were chosen to observe the effects of cladding on the adhesion of the Teflon to the different surfaces as well as effects on the corrosion properties. For comparison of aging processes on heat effects, two other aluminum alloys were selected; the 6061-T6 alloy, which has been heat treated and artificially aged at elevated temperatures, and the 5052-H32 alloy, which has been cold worked for better ductility than the other two alloys and one-quarter strain-hardened. The only magnesium alloy tested was AZ31B-H24 since it is the alloy primarily used in aircraft construction. The chrome pickled samples were used to estimate effects of chrome pickling on adhesion of the Teflon coating and on corrosion resistance.

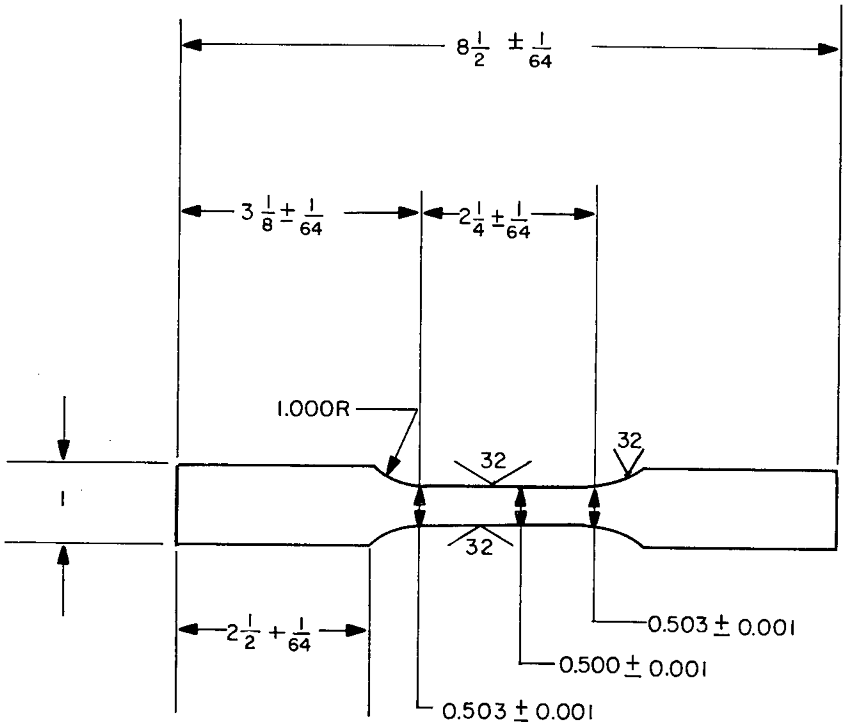

Fig. 1 - Tensile test specimen

The alloy samples, approximately 1/16 inch thick, were cut into strips measuring 8-3/4 inches by 11/16 inch and then milled to a standard sheet metal specimen (Fig. 1). The tensile specimens used for controls, the chrome-pickled magnesium alloys, as well as the clad 2024-T3 aluminum were washed with xylene before testing. Specimens used for the other tests were cleaned by sandblasting with a fine grit sand. The process also gives a satin finish, conducive to good adhesion. A xylene wash was used to remove traces of sand or metal particles remaining. All samples were dried in a 50°C oven for one hour prior to application of the Teflon coating.

The procedure fully described in NAVWEPS OD 23684 and other reports (3,4,5) was followed in the application of the coatings. The commercially available Teflon spray formulation used was DuPont's Teflon one-coat green enamel (No. 851-204). The measured pH of the formulation was 1.5. The filtered formulation was sprayed on the metals with a DeVilbiss EGA Series spray gun with an F nozzle at 25 to 30 psi air pressure. An approximately 0.0002 to 0.0004 inch thick coating was applied to one side of the test specimen; approximately 1 inch was left uncoated on both ends. The sprayed samples were dried in the air overnight and then in an oven at 50°C for one hour.

To evaluate oven fusion, the samples were placed in a preheated air-circulating oven for 12 minutes at 750°F. The temperature, higher than recommended, was used to heighten the effect on mechanical properties. After the heating period, the test specimens were air cooled to room temperature.

For flame fusion, a natural gas-air flame served as a concentrated source of heat. A National Welding Company Type 3A blowpipe torch fitted with a W-2 nozzle was used to produce a flame of 1-1/2 inches overall length with an inner cone tip of one inch measured from the end of the torch (Fig. 2). The flame temperature 1/8 inch in front of the inner cone was 2660°F (1460°C) as measured by a platinum vs. platinum-rhodium (1%)

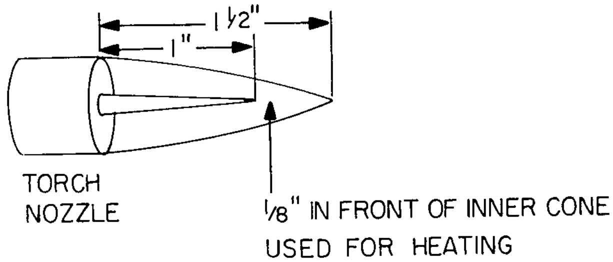

Fig. 2 - Typical flame

thermocouple. The flame was directed upon the specimen, passed across the surface at a rate of approximately one inch per second, then swept across the panel in the reverse direction, and finally passed over the same path for a third time. The Teflon usually fused during the last sweep. After fusion, the test specimens were air cooled to room temperature. The Teflon fusion was accompanied by a color or shade change of the applied coating in the area just following behind the flame. In the case of the Teflon green enamel, the color change was from a yellowish-green to a darker green. The uncoated specimens lacked this indicator change; data for such samples show that reproducibility is poor.

Proper fusion of the Teflon was tested by the application of pressure-sensitive tape to the coated surface and rapidly pulling it off. A properly fused coating will not be removed by the tape. This test was used for both the oven-fusion and flame-fusion procedures.

The tensile strengths and yield strengths of each alloy were determined after the following treatments:

1. Untreated (control).
2. Uncoated, oven heated.
3. Uncoated, flame heated.
4. Coated with Teflon, oven fused.
5. Coated with Teflon, flame fused.

The tensile strengths and yield strengths were determined with an Instron Tensile Tester Model TTC at a crosshead speed of 0.5 inch per minute.

RESULTS AND DISCUSSION

The data from control specimens were compared with the data of all the treated specimens (Tables 1-6). The differences in average tensile strengths (ΔT) and in average yield strengths (ΔY) are depicted in Fig. 3; similarly the percent reductions, based on the data from control samples, are summarized in Fig. 4. Figures 3 and 4 show that the flame method has less effect on engineered mechanical properties than the oven heating at 750°F. The data show that the method of heating is the most important variable; this applies to all alloys studied, coated and uncoated.

The data in Tables 1 through 6 show that the standard deviations of the heated specimens were generally within the range observed for the control specimens. When different persons repeated the flame and oven heating procedures, pooling of their data gave standard deviations that were no different from those noted for the controls. Thus, the observed differences in mechanical properties between heating methods are not due to variations in test samples nor the persons conducting the tests. The larger standard deviations noted for flame-heated samples when compared to oven-heated samples indicates that the hand-flame method is more difficult to reproduce. The standard deviations were larger than

Table 1
Mechanical Properties of Magnesium Alloy AZ31B-H24

	No. of Samples Tested	Average Tensile Strength			Average Yield Strength		
		T (psi × 10^{-3})	Decrease ΔT		Y (psi × 10^{-3})	Decrease ΔY	
			(psi × 10^{-3})	(%)		(psi × 10^{-3})	(%)
Literature*	-	42.0	-	-	32.0	-	-
Control	13	41.1 ± 0.6	-	-	31.4 ± 1.2	-	-
Uncoated							
Oven heated	6	37.0 ± 0.6	4.1	10.0	20.1 ± 0.6	11.3	36.0
Flame heated	6	37.9 ± 0.3	3.2	7.8	22.8 ± 1.2	8.6	27.4
Coated							
Oven fused	6	36.3 ± 0.2	4.8	11.7	20.2 ± 0.7	11.2	35.7
Flame fused	6	36.9 ± 0.5	4.2	10.2	21.8 ± 1.5	9.6	30.6

*T. Lyman, editor, "Properties and Selection of Metals," Vol. 1 of "Metals Handbook," 8th edition, Novelty, Ohio:Am. Soc. of Metals, p. 1107, 1961.

Table 2
Mechanical Properties of Magnesium Alloy AZ31B-H24
With Chrome Pickle

	No. of Samples Tested	Average Tensile Strength			Average Yield Strength		
		T (psi × 10^{-3})	Decrease ΔT		Y (psi × 10^{-3})	Decrease ΔY	
			(psi × 10^{-3})	(%)		(psi × 10^{-3})	(%)
Literature*	-	42.0	-	-	32.0	-	-
Control	20	42.1 ± 1.0	-	-	35.2 ± 1.3	-	-
Uncoated							
Oven heated	9	37.1 ± 0.2	5.0	11.9	21.9 ± 0.6	13.3	37.8
Flame heated	3	37.8 ± 0.2	4.3	10.2	21.3 ± 0.0	13.9	39.5
	6†	39.8 ± 1.1	2.3	5.5	26.5 ± 1.5	8.7	24.7
Coated							
Oven fused	9	36.8 ± 0.6	5.3	12.6	21.8 ± 1.5	13.4	38.0
Flame fused	6	36.9 ± 0.8	5.2	12.3	22.3 ± 1.0	12.9	36.6
	7†	40.2 ± 1.5	1.9	4.5	31.4 ± 1.7	3.8	10.8

*T. Lyman, editor, "Properties and Selection of Metals," Vol. 1 of "Metals Handbook," 8th edition, Novelty, Ohio:Am. Soc. of Metals, p. 1107, 1961.

†Specimens treated with a hotter flame and faster sweep rate than others.

Table 3
Mechanical Properties of Aluminum Alloy 2024-T3

	No. of Samples Tested	Average Tensile Strength			Average Yield Strength		
		T (psi × 10^{-3})	Decrease ΔT (psi × 10^{-3})	Decrease ΔT (%)	Y (psi × 10^{-3})	Decrease ΔY (psi × 10^{-3})	Decrease ΔY (%)
Literature*	-	70.0	-	-	50.0	-	-
Control	15	70.9 ± 1.0	-	-	51.4 ± 1.0	-	-
Uncoated							
Oven heated	3	45.5 ± 0.2	25.4	35.8	20.3 ± 0.6	31.1	60.5
Flame heated	3	61.2 ± 2.8	9.7	13.7	47.4 ± 4.7	4.0	7.8
Coated							
Oven fused	3	47.4 ± 0.2	23.5	33.1	19.8 ± 0.1	31.6	61.5
Flame fused	5	60.4 ± 1.1	10.5	14.8	46.7 ± 1.5	4.7	9.1

*T. Lyman, editor, "Properties and Selection of Metals," Vol. 1 of "Metals Handbook," 8th edition, Novelty, Ohio:Am. Soc. of Metals, p. 940, 1961.

Table 4
Mechanical Properties of Aluminum Alloy 2024-T3, Clad

	No. of Samples Tested	Average Tensile Strength			Average Yield Strength		
		T (psi × 10^{-3})	Decrease ΔT (psi × 10^{-3})	Decrease ΔT (%)	Y (psi × 10^{-3})	Decrease ΔY (psi × 10^{-3})	Decrease ΔY (%)
Literature*	-	70.0	-	-	50.0	-	-
Control	5	69.3 ± 0.6	-	-	49.2 ± 1.0	-	-
Uncoated							
Oven heated	3	44.3 ± 0.0	25.0	36.1	17.4 ± 0.0	31.8	64.6
Flame heated	3	64.9 ± 2.5	4.4	6.3	42.9 ± 4.0	6.3	12.8
Coated							
Oven fused	3	45.0 ± 0.0	24.3	35.1	18.5 ± 0.4	30.7	62.4
Flame fused	7	66.1 ± 2.0	3.2	4.6	45.4 ± 3.8	3.8	7.7

*T. Lyman, editor, "Properties and Selection of Metals," Vol. 1 of "Metals Handbook," 8th edition, Novelty, Ohio:Am. Soc. of Metals, p. 940, 1961.

Table 5
Mechanical Properties of Aluminum Alloy 5052-H32

	No. of Samples Tested	Average Tensile Strength			Average Yield Strength		
		T (psi × 10^{-3})	Decrease ΔT		Y (psi × 10^{-3})	Decrease ΔY	
			(psi × 10^{-3})	(%)		(psi × 10^{-3})	(%)
Literature*	-	33.0	-	-	28.0	-	-
Control	11	34.9 ± 0.5	-	-	29.0 ± 0.9	-	-
Uncoated							
Oven heated	4	28.4 ± 0.2	6.5	18.6	9.0 ± 0.4	20.0	69.0
Flame heated	4	32.5 ± 1.0	2.4	6.9	20.8 ± 1.9	8.2	28.3
Coated							
Oven fused	6	29.4 ± 1.1	5.5	15.8	9.0 ± 0.5	20.0	69.0
Flame fused	6	31.0 ± 1.1	3.9	11.2	18.8 ± 0.7	10.2	35.2

*T. Lyman, editor, "Properties and Selection of Metals," Vol. 1 of "Metals Handbook," 8th edition, Novelty, Ohio:Am. Soc. of Metals, p. 943, 1961.

Table 6
Mechanical Properties of Aluminum Alloy 6061-T6

	No. of Samples Tested	Average Tensile Strength			Average Yield Strength		
		T (psi × 10^{-3})	Decrease ΔT		Y (psi × 10^{-3})	Decrease ΔY	
			(psi × 10^{-3})	(%)		(psi × 10^{-3})	(%)
Literature*	-	45.0	-	-	40.0	-	-
Control	21	46.1 ± 0.6	-	-	41.9 ± 1.3	-	-
Uncoated							
Oven heated	6	22.7 ± 0.2	23.4	50.8	7.9 ± 0.1	34.0	81.1
Flame heated	3	32.9 ± 0.5	13.2	28.6	25.4 ± 0.8	16.5	39.4
Coated							
Oven fused	6	22.5 ± 0.2	23.6	51.2	8.0 ± 0.2	33.9	80.9
Flame fused	5	32.1 ± 0.6	14.0	30.4	25.3 ± 1.4	16.6	39.6

*T. Lyman, editor, "Properties and Selection of Metals," Vol. 1 of "Metals Handbook," 8th edition, Novelty, Ohio:Am. Soc. of Metals, p. 946, 1961.

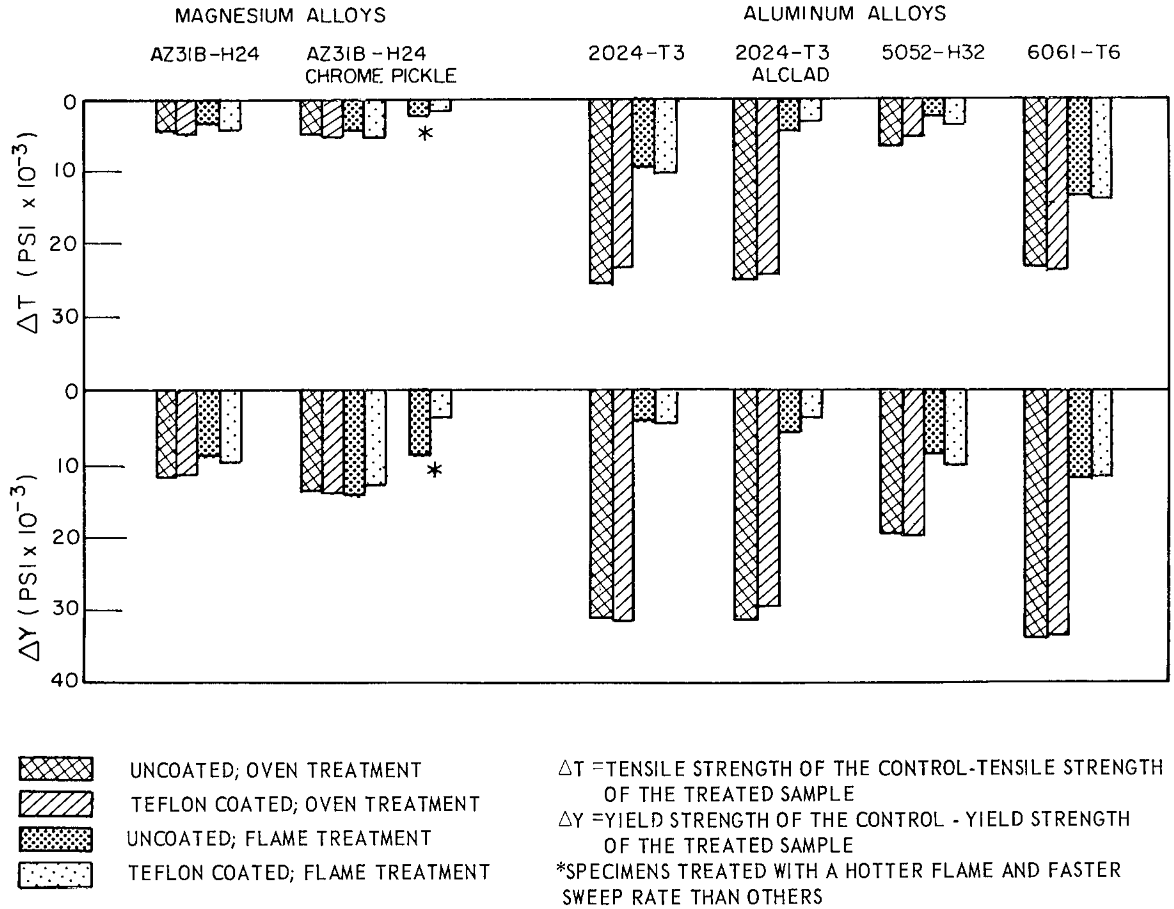

Fig. 3 - Decrease of tensile and yield strength of Teflon-coated and uncoated magnesium and aluminum alloys

the control sample values for uncoated, flame-heated aluminum alloys 2024-T3 (Table 3), 2024-T3 (clad)(Table 4), and 5052-H32 (Table 5). The poor reproducibility noted for these samples can be explained by the absence of the convenient shade change that accompanies the Teflon fusion of coated samples. The shade change occurring when the Teflon fuses, was helpful in establishing the optimum flame sweep rate over Teflon-coated magnesium alloy AZ31B-H24 (Table 2). The faster sweep and shorter exposure time significantly reduced the heat effects on the as-received mechanical properties.

Effects of heating were difficult to ascertain in some cases because of the small difference between the averages to be compared. The $\underline{t}$ test of statistics was applied to evaluate such data; the calculated $\underline{t}$ values, the ratio of the difference between the averages to the standard deviation of this difference, are listed in Table 7. The $\underline{t}$ values of results that appeared to be the same (2024-T3, clad, flamed) and different (2024-T3, clad, Teflon coated) are included. Samples with tensile strengths that differ, but yield strengths that show no difference are noted for magnesium alloy AZ31B-H24, coated and uncoated, and aluminum alloy 2024-T3, clad and unclad. The value for aluminum alloy 5052-H32 shows a reverse relationship of the tensile and yield strengths. The large $\underline{t}$ values calculated for magnesium alloy AZ31B-H24, fast flame sweep and slow flame sweep, indicates that the fast flame sweep rate causes a significantly smaller decrease in tensile and yield strengths.

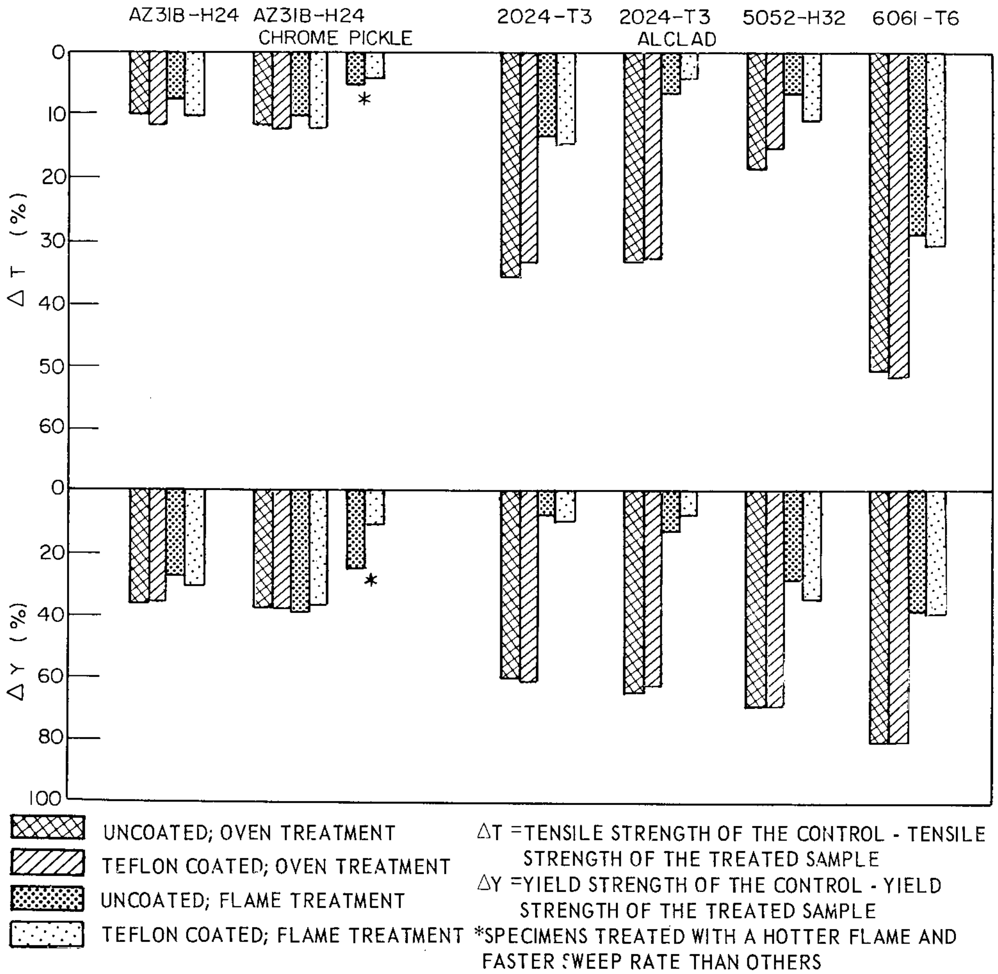

Fig. 4 - Percent decrease of tensile and yield strength of Teflon-coated and uncoated magnesium and aluminum alloys

The flame, or concentrated heat, method of heating involves a rapid increase in temperature; maintenance of a high temperature until fusion has occurred (estimated time interval at the maximum temperature is less than a second) and then unaided cooling of the test specimen to ambient temperature. The authors could find no data on comparable heat treatments for the alloys studied. Consequently, only a qualitative comparison can be made between the available literature data and that reported here.

The Dow Chemical Company (9) has reported the mechanical properties of magnesium alloy AZ31B-H24 after 16, 18, 192, 500, and 1,000 hours at temperatures ranging from 200°F to 600°F. The data for the mechanical properties after 16 hours heating at various temperatures have been plotted in Fig. 5. The 600°F values compared to those listed for unheated samples show a 13% reduction of tensile strength, a 30% reduction of yield strength, and a 25% reduction of the elongation. The data in Tables 1 and 2 indicate that shorter heating periods at higher temperatures give comparable results. The exceptions noted in Table 2 are those values obtained from samples which were heated with a hotter flame and a faster sweep rate than other flame-heated samples. Specimens coated with Teflon and so fused exhibited a significantly smaller reduction in mechanical properties than the other samples, viz., 4.5% reduction of tensile strength and 10.8% reduction of the yield strength. The shortened exposure time at higher temperatures gave a good coating as indicated by the tape test. Magnesium alloy AZ31B-H24 sheet, 0.064 inch thick, has

Table 7
t Test Applied to Average Tensile and Yield Strengths

Alloy and Treatment	Degrees of Freedom	Average Tensile Strength (psi × 10^{-3})	Calculated t value	Probability Level (Percent)	Average Yield Strength (psi × 10^{-3})	Calculated t value	Probability Level (Percent)
AZ31B-H24, Flamed	10		4.20	0.1		0.95	not significant
Teflon Coated		36.9			21.8		
Uncoated		37.9			22.8		
2024-T3, Teflon Coated, Flamed	10		5.66	0.1		0.72	not significant
Clad		66.1			45.4		
Unclad		60.4			46.7		
5052-H32, Teflon Coated	10		2.18	about 6		27.85	0.1
Oven fused		29.4			9.0		
Flame fused		31.0			18.8		
AZ31B-H24, Chrome Pickle, Flamed	11		4.88	0.1		11.16	0.1
Fast flame sweep		40.2			31.4		
Slow flame sweep		36.9			22.3		
2024-T3, Clad, Flamed	8		0.81	not significant		0.82	not significant
Teflon coated		66.1			45.4		
Uncoated		64.9			42.9		
2024-T3, Clad, Teflon Coated	8		9.21	0.1		11.89	0.1
Oven fused		45.0			18.5		
Flame fused		66.1			45.4		

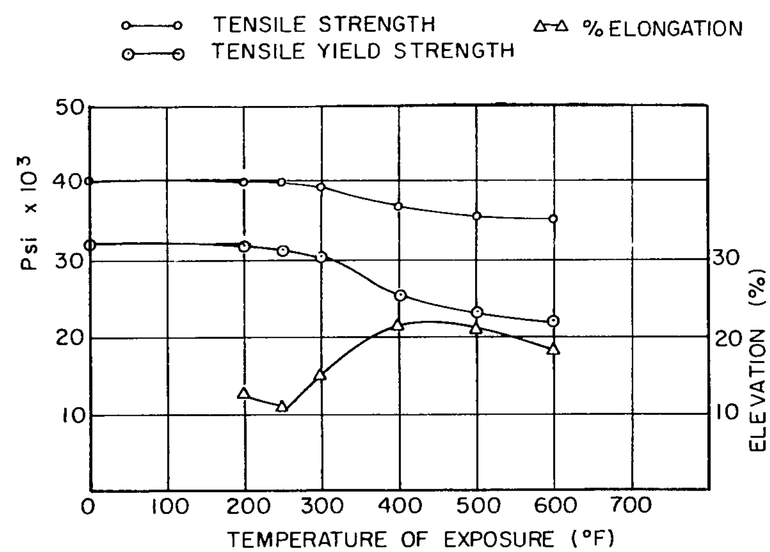

Fig. 5 - Mechanical properties of AZ31B-H24 sheet at room temperature after 16 hours at elevated temperatures (Ref. 9)

Table 8
Thermal Conductivities and Heat Capacities

	Thermal Conductivity at 25°C Cal/(Sec)(Cm^2)(°C/Cm)	Heat Capacity at 100°C Cal/(g)(°C)
Water*	0.0015	1.01
Paper†	0.0003	0.3-0.4‡
Teflon §	0.0006	0.25
AZ31B-H24¶	0.23	0.26
2024-T3**	0.45	0.23
5052-H32††	0.33	0.23
6061-T6‡‡	0.41	0.23

*C. Hodgman, editor, "Handbook of Chemistry and Physics," 43rd edition, Cleveland, Ohio:Chemical Rubber Publishing Co., p. 2476, 1961.

†C. Hodgman, editor, "Handbook of Chemistry and Physics," 43rd edition, Cleveland, Ohio:Chemical Rubber Publishing Co., p. 2473, 1961.

‡Estimated from values given for wood and celluose in R.H. Perry, editor, "Chemical Engineers Handbook," 4th edition, New York:McGraw Hill, sec. 3, p. 133, 1963.

§Insulation 10(May/June)(1964).

T. Lyman, editor, "Properties and Selection of Metals," Vol. 1 of "Metals Handbook," 8th edition, Novelty, Ohio:Am. Soc. of Metals, 1961:
¶p. 1107.
**p. 940.
††p. 943.
‡‡p. 946.

been reported (10) to maintain the engineered mechanical properties at a temperature of 500°F for a maximum exposure period of 0.3 minute (18 seconds). Data for higher temperatures and shorter exposure periods were not found for magnesium or aluminum alloys.

Data in Tables 3-6 show greater differences between the oven-heated and flame-heated samples of aluminum alloys than for the magnesium alloy. The 2024-T3 aluminum alloy (heat treated, naturally aged, and cold worked) is changed least when the flame method is used to fuse the Teflon coating. The 6061-T6 aluminum alloy (artificially aged at elevated temperatures) shows the greatest sensitivity to heat. The cold-worked aluminum alloy 5052-H32 shows an intermediate effect.

The flame or concentrated heat applied to a metal surface covered with a thin film of relatively low thermal conductivity, is analogous to a Bunsen burner flame used to heat water in a thin paper cup. The higher thermal conductivity (Table 8) and heat capacity of the water compared to the paper allows heat to be dissipated by the contained water; the paper in contact with the water stays relatively cool whereas an outer lip of paper, exposed only to air, will readily char or burn. Although the flame temperature may be 300° to 400°C at the bottom of the cup, the paper in contact with the water will be maintained at approximately 100°C when the water reaches its boiling point. Heat is consumed by the phase transformation, liquid to vapor, as the water boils.

A thin coating film on a metal surface will act similarly to the paper cup. However, the phase change (solid to liquid) temperatures for metals are relatively high compared to the decomposition temperatures of most organic coatings. Though high thermal conductivity indicates that the metal will dissipate applied heat away from the film, the coating may be overheated because there is no metal phase change below the decomposition temperatures of the organic film. The film on a metal surface can be fused without decomposition at high temperatures (2660°F as in this report) only if the exposure time is short, that is, a second or less. The success of the flame method is primarily a matter of bringing the coating to a fusing temperature while the bulk metal never attains that temperature.

It was initially noted that with magnesium alloy AZ31B-H24 there was no significant difference between the flame and oven heating. The low thermal conductivity, nearly 50% lower than the aluminum alloys, could cause overheating of the metal when the same flame sweep rate as for the aluminum alloys was used. The slower heat dissipation is compensated by using a hotter flame and increasing the flame sweep rate; these procedures favor a faster rate of Teflon fusion with a shorter exposure of the alloy to high temperatures. The success of this modified procedure is evident from Table 2 and the data summarized in Figs. 3 and 4.

CONCLUSIONS AND FUTURE WORK

The flame method has been used successfully in the fusing of Teflon on a metal surface; the smaller changes in mechanical properties than when oven heated suggest a concentrated heat method as a means for thermally curing coatings on structural metals. We have found that the method of thermal curing may be of most value with aluminum alloy 2024-T3. We feel that thermal conductivity and heat capacity of the substrate are important and must be considered for each substrate in order to provide the proper flame temperature and flame sweep rate.

At present the reproducibility of the results is limited by the hand technique. An automatic conveyor system, incorporating an automatic traverse of a flame or other sources of concentrated heat with multiple heating units engineered to accomplish the heating would provide uniform control. Other heat sources that can be focused to relatively small areas could be used, e.g., laser beams and infrared; of course under proper automation large areas may be heated. The possibilities of a heat dissipator, e.g., circulated water or air on the uncoated side is suggested for further investigation.

Currently, we are investigating new protective systems that require thermal treatments during their application. They were chosen for their possible ability to arrest the corrosion of magnesium alloys in a marine environment. Although this investigation was not meant to study a protective system of Teflon, several test samples of magnesium and aluminum alloys were evaluated for corrosion resistance by the 3% sodium chloride immersion test (11).

The trends indicated by the flame technique are encouraging. We feel, however, that there are many aspects of the problem involved that have not been covered by this current study. For examples: the effect of metal thickness when the flame method is used; local heating effects; and strains set up in the metal by the flame method. Data, similar to that compiled for longer exposure times at lower temperatures, are needed for the high-temperature, short-duration conditions reported here. Further data is needed to explain why the aluminum alloy 6061-T6 (artificially aged at elevated temperatures) showed the greatest percent reduction in mechanical properties when compared to the other aluminum alloys that were cold worked. We need information on the effect of the flame method on the mechanical properties of annealed alloys. But we are concerned with the development of a coating system for alloy protection, so we do not plan to investigate further these problems which are primarily metallurgical.

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Changes in the tensile and tensile yield strengths after fusing Teflon on magnesium alloy AZ31B-H24, and aluminum alloys 2024-T3, 5052-H32, and 6061-T6 have been studied. The new technique, a flame technique, for fusing Teflon caused less alteration of the mechanical properties than the frequently used 750°F oven method; aluminum alloy 2024-T3 was affected less than the other alloys. The flame or concentrated source of heat is superior to the oven method of heating because the high temperatures used are such that a rapid fusion of the coating can be accomplished without heating the bulk metal to the fusion or decomposition temperature of the coating. The new technique appears applicable to other coatings and substrates, although the thermal conductivities and heat capacities of the substrate and coating must be considered when optimum flame-fusion conditions are sought.

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