Improvement in Fatigue Resistance of Aluminum Alloys by Surface Cold-Working

By G. A. BUTZ and J. O. LYST

These tests show that surface rolling and peening can have a large effect on fatigue resistance of aluminum alloys. The amount of this effect depends on the material and the stress situation, being greatest where sharp stress gradients, such as are associated with notches, are present. Under axial stressing of smooth specimens there was very little, if any, effect. Service abuse was simulated in several ways, including notches, corrosion, and unfavorable residual stresses. In some situations, the indicated specimen strength was more than doubled. Proper prestressing specifications are shown to be related to the type of surface and stress distribution. Reductions in effect associated with heating after prestressing are briefly explored.

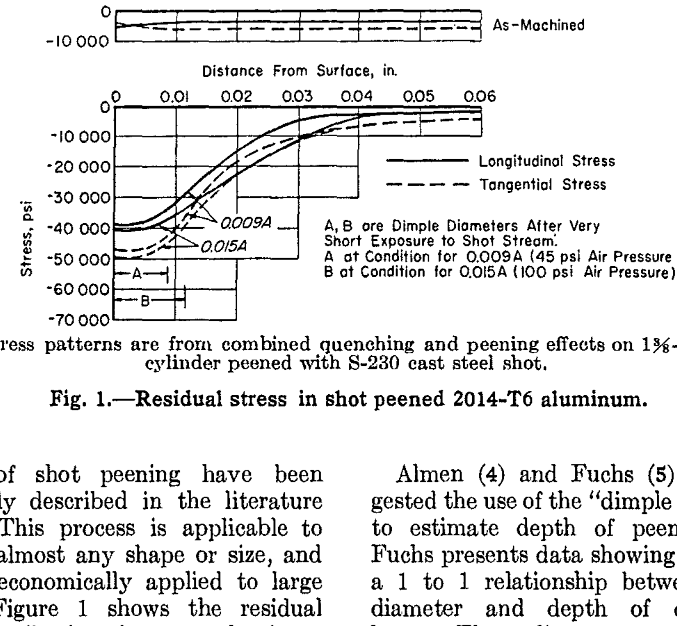
It has been known for many years that the fatigue resistance of metal parts can be improved by surface cold working. However, it has only been in recent years that the procedure has been widely used. Today, it is used to some degree in a very large proportion of the cars, trucks, and airplanes produced in this country, and has found wide application in many other fields. The tests reported here were not conceived as an integrated attempt to investigate thoroughly all aspects of surface cold working, but rather were a series of programs designed to answer specific questions.

Mechanical surface cold working is accomplished by local plastic yielding of the surface layers. The most common methods are shot peening and surface rolling. In these operations, by virtue of a localized pressure, the surface metal is stressed beyond its elastic limit. When the pressure is removed, the surface layers retain part of the deformation experienced under pressure. Subsurface material which has not exceeded the elastic limit attempts to force the surface elements to return to their original length, thereby inducing a surface residual stress which is compressive. Since the surface layers are deformed plastically, their metallurgical characteristics are affected. The finish and geometrical character of the surface may also be changed. Each of these three effects may influence fatigue performance. Independent assessment is extremely difficult and beyond the scope of this paper, although some data pertaining to each are included. Essentially, this paper is concerned with the actual fatigue performance of test specimens, cold worked in various ways and to different degrees, in varied environmental situations.

Surface Working Processes

Shot Peening

The nomenclature, specifications, and control of shot peening have been adequately described in the literature (1–3).[1] This process is applicable to parts of almost any shape or size, and may be economically applied to large areas. Figure 1 shows the residual stress distribution in two aluminum alloy cylinders peened with one size of shot to two different intensities. The stress patterns were similar for the two intensities, with a tendency for higher stresses and increased depth of effect for the heavier intensity.



NOTE.—Stress patterns are from combined quenching and peening effects on 1⅜-in. diameter cylinder peened with S-230 cast steel shot.

Fig. 1.—Residual stress in shot peened 2014-T6 aluminum.

Almen (4) and Fuchs (5) have suggested the use of the "dimple diameters" to estimate depth of peening effect. Fuchs presents data showing essentially a 1 to 1 relationship between dimple diameter and depth of compressed layer. These diameters were checked for the peening conditions of the specimens of Fig. 1, and are indicated by dimensions A and B. The residual stresses decrease rapidly beyond the depths equal to these dimple diameters.

Figure 2 from Brodrick (6) shows the

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[1] The boldface numbers in parentheses refer to the list of references appended to this paper.

relation between shot size and depth to which compressive residual stresses are maintained. This shows that maximum depths are obtained by relatively large shot and high intensities. The magnitude of the surface compressive stress did not vary consistently with shot size, but was typically a large fraction of the material's yield strength.

Surface Rolling

Surface rolling is most commonly applied to surfaces of revolution. While outside diameters of cylinders, with or without fillets, are the largest application, inside diameters and flat circular areas have also been rolled. Figure 3 shows a fatigue test specimen being rolled in a lathe.

Figure 4 illustrates the residual stress patterns in two aluminum alloy cylinders rolled with the same roller at different loads and feeds. The smaller load of 25 lb gives a maximum computed ("elastic") contact stress of 250,000 psi. This contact stress is proportional to the cube root of the load; therefore, its magnitude at the 8-times-heavier 200-lb load is twice this, or 500,000 psi. There is considerable difference between the stress patterns resulting from the two conditions. Those resulting from the lighter load are smaller and extend to less depth; the longitudinal and tangential stresses are almost identical for the lighter load, but considerably different for the heavier.

Figure 5 is a micrograph of a sample from the surface of a rolled 2024–T4 specimen. The sample was treated to show the cold working of the surface by revealing the recrystallized structure after reheat treating. The depth of the obviously recrystallized layer is about 0.010 in. The depth of compressive stress in this sample was considerably greater than this.

Attempts have been made to observe a change in surface hardness due to rolling. In aluminum-alloy specimens heat treated to near maximum hardness, then heavily rolled, no effect has been conclusively detected, even with the more superficial hardness techniques such as Rockwell 15-T or 30-T.

Figure 6 shows the effect of roller contour radius and load on specimen surface roughness. The graph at the left shows that roughness is greater for higher loads and smaller contour radii. Generally, however, lighter loads are used for the smaller-radius rollers. The dashed line on this figure joins the loads on each curve where a maximum computed ("elastic") contact stress of 500,000 psi is attained (7). The right-hand graph shows the tendency toward improvement in surface finish as feed is reduced.

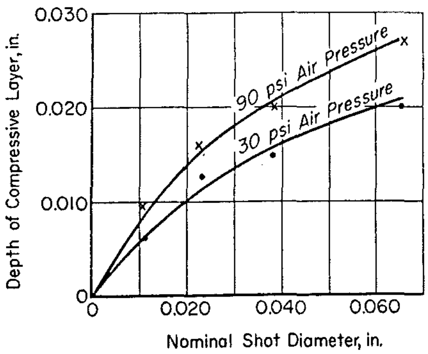


Fig. 2.—Effect of shot size on depth of compressive layer in 7076-T6 aluminum (from reference (6)).

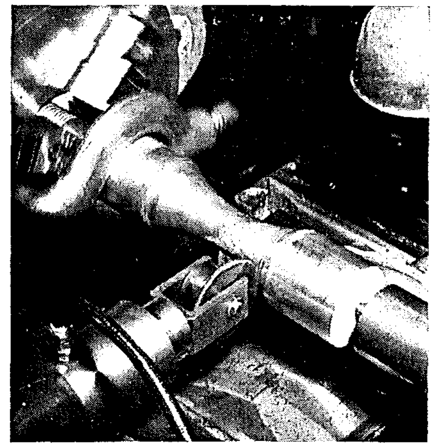
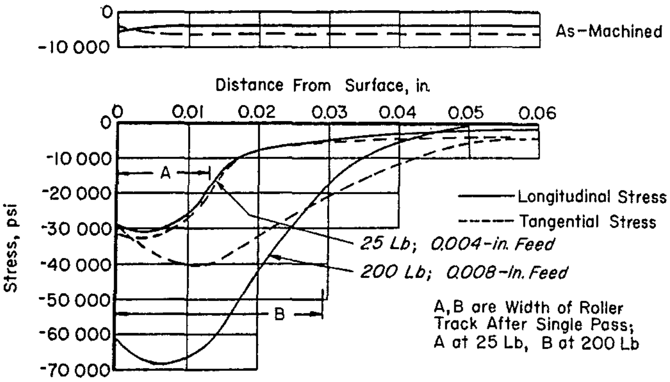


Fig. 3.—Surface rolling of fatigue specimen.



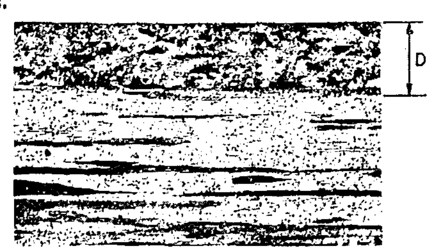
NOTE.—Stress patterns are from combined quenching and rolling effects on $1\frac{3}{8}$-in. diameter cylinder rolled with 3-in. diameter by $\frac{1}{16}$-in. radius roller.

Fig. 4.—Residual stress in surface-rolled 2014-T6 aluminum alloy at two rolling intensities.

Cold-Working Specifications and Fatigue Resistance

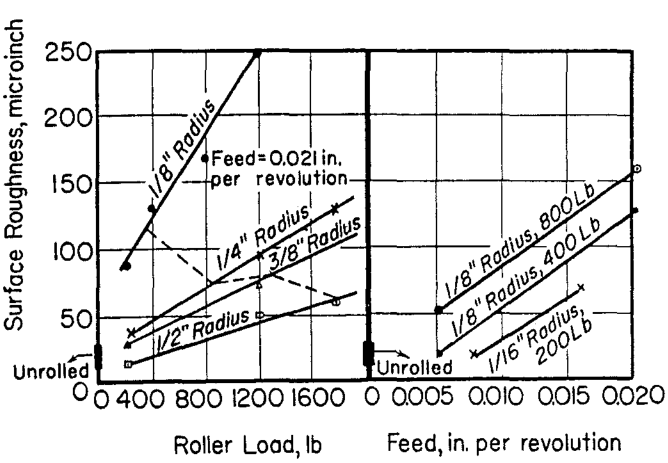
General

The series of tests reported in this section were conducted at Alcoa to show, in a general way, the influence of surface cold working in accordance with certain specifications on fatigue resistance. Most of the work was on 2014-T6 alloy, but several other wrought alloys and one representative casting alloy have been evaluated more



NOTE.—22-in. diameter cylinder with $\frac{7}{16}$-in. wall; rolled with 3-in. diameter by $\frac{1}{16}$-in. radius roller at 200 lb; Keller's etch. (×100), reduced one half in reproduction.

Fig. 5.—Cold work in surface layers of rolled 2024-T6 aluminum alloy shown by recrystallization depth (D).



NOTE.—$1\frac{3}{8}$-in. diameter specimen; $\frac{1}{16}$-in. radius roller is 3-in. diameter, others are $1\frac{3}{8}$-in diameter. Oil-lubricated during rolling.

Fig. 6.—Effect of roller load and feed on surface finish of 2014-T6.

briefly. Most tests were designed to produce failure in a medium-cycle life range, between 100 thousand and 10 million cycles. In all cases, control data were obtained from "as-machined" specimens in both the notched and unnotched conditions, and the cold worked specimens were tested both with and without subsequent notching. The purpose of this notching was to simulate the many design or service situations where surface cold working might be expected to mitigate harmful effects of surface damage that may occur after the part is placed in use. Notches were cut with a 60-deg V-shape tool producing a root radius of less than 0.001 in. The stresses quoted are based on the section modulus at the root of the notch.

In the interest of making many of these data more understandable and to illustrate trends, such terms as "life factors" and "strength improvements" are used. These terms are somewhat ambiguous, since they are dependent on the relative position of the data on the *S-N* curve. Life factors are used when comparisons were at similar stresses, and strength factors when at similar lives.

Shot Peening

Table I shows the improvements in specimens shot peened and tested without notching. The "fatigue strength improvement" is the percentage by which a stress for a shot-peened specimen exceeds the stress at which a typical control specimen failed at that same life. A considerable range of shot size and intensity is represented in the 2014-T6 specimens, but all results are in a fairly small bracket of 18 to 29 per cent improvement with no obvious correlation of specifications and results. With the 2024-T4 specimens, the improvement was somewhat larger. No further improvement was indicated as a result of "over-peening" with fine shot.

Figure 7 illustrates the effect of peening intensity with a particular shot size on the fatigue life of specimens notched after peening. There are two special points on this figure. One shows that the intense cold working by a $\frac{1}{8}$-in. radius tool in an air hammer gave a very large life increase. A specimen peened after notching showed a much larger improvement than a companion specimen peened before notching. The No. S-230 shot gave effective resistance to the 0.010-in. deep notch, although the intensity needed to be high for improvement. With the 0.020-in. notch, the low peening intensities were ineffectual, but higher ones were helpful. This size shot is not capable, however, of giving the protection afforded by very heavy peening, as shown by the tool-peened specimen. Thus, either shot size or intensity or both must increase as notch depth increases to realize the potential protection offered by shot peening.

Surface Rolling

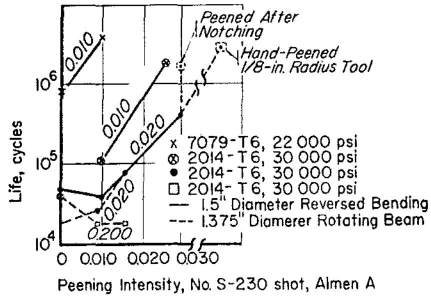
Table II summarizes the performance of unnotched specimens after various conditions of rolling. The range of conditions covered by these tests can be better appreciated by reference to Fig. 8. These two specimens were the extremes in working, appearance, and surface roughness. One had a surface roughness of 14 microinches; the other surface was too rough to measure by the method used. Yet, the life of the rougher one was 50 per cent greater under the same test conditions.

Table III shows the relation between intensity of rolling and life improvement ratio at a given stress level, for specimens notched after rolling. At

TABLE I.—FATIGUE RESISTANCE OF UNNOTCHED SPECIMENS AT VARIOUS SHOT-PEENING CONDITIONS.

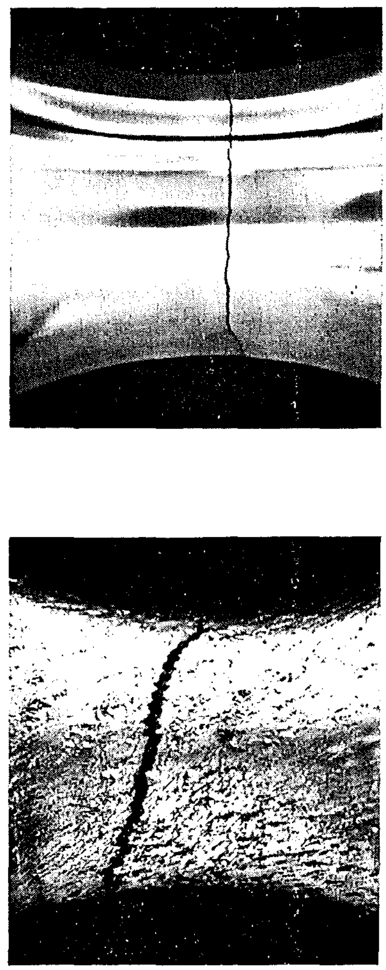
Shot Size	Intensity	Fatigue Strength Improvement, per cent
	2014-T6	
S-70	0.006 A	21, 29[a]
S-230	0.009 A	24
S-230	0.016 A	24
S-230	0.028 A	18 to 24[b]
S-550	0.013 A	20
	2024-T4	
S-230	0.010 A	33 to 39[c]
S-230	0.015 A +	32 to 43[b]
S-70	0.006 A	32 to 43[b]
	Overpeened	32 to 43[b]

NOTE.—1.5-in. diameter specimens tested in reversed bending. Failures in 0.6 to 6 million cycles.
[a] Two specimens tested.
[b] Three specimens tested.
[c] Four specimens tested.



NOTE.—Figures on curves are notch depths in inches.

Fig. 7.—Effect of shot peening on subsequently notched specimens.



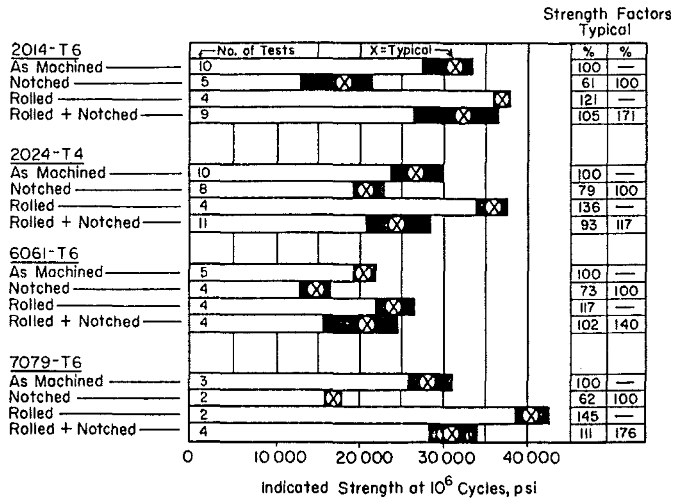
(*top*) Rolled with ½-in. radius by 1.375-in. diameter roller, 200-lb load, 0.021-in. feed. Surface roughness, 14 microinches. Stress, 27,000 psi. Cycles at failure, 7.4 million.
(*bottom*) Rolled with ⅛-in. radius by 1.375-in. diameter roller, 1800 lb load, 0.010-in. feed. Stress, 27,000 psi. Cycles at failure, 10.6 million.

Fig. 8.—2014-T6 fatigue specimens of 1.375-in. diameter rolled under widely different conditions.

TABLE II.—EFFECT OF ROLLING CONDITIONS ON FATIGUE RESISTANCE OF 2014-T6 ALLOY.

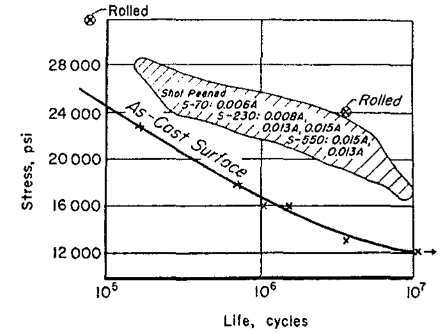
Roller Contour Radius, in.	Roller Feed, in.	Roller Load, lb	Maximum Compressive, Stress, thousands of psi	Indicated "Strength Improvement," per cent
1/16	0.008	30–300	260 to 570	11 to 18
1/16	0.004	300–600	570 to 720	22 to 36
⅛	0.021	200–1800	410 to 860	25 to 32
⅛	0.010	200–1800	410 to 860	25 to 30
⅛	0.005	400–800	520 to 660	25 to 26
¼	0.021	200–1800	300 to 650	22 to 30
⅜	0.021	200–1800	270 to 560	25 to 31
½	0.021	200–1800	240 to 500	27 to 32
Extreme values (minimum, maximum)				11, 32
Over-all average				27

NOTE.—Specimens rolled with 1/16-in. radius roller were 1.5-in. diameter, tested in reversed bending. Others were 1.375-in. diameter, tested in rotating bending. Failures in 1- to 20-million cycle range.



NOTE.—1.5-in. diameter specimen in reversed bending. Rolled with 3-in. diameter by $\frac{1}{16}$-in. radius roller at 200 lb load and 0.008-in. feed. Notch 0.020-in. deep.

Fig. 9.—Effect of one rolling condition on the fatigue resistance of four wrought alloys.



NOTE.—1.5-in. diameter specimen tested in reversed bending. C 355-61 T alloy cast by premium process. Rolled with 3-in. diameter by $\frac{1}{16}$-in. radius roller at 200 lb load and 0.008-in feed.

Fig. 10.—Effect of peening and rolling on cast aluminum.

the two highest roller loads, the life of the rolled and 0.020-in. notched specimen was much greater than that of the as-machined specimen without a notch. Specimens with a very deep notch (0.200 in.) showed a definite, but lesser life improvement. Very heavy rolling would be necessary for large improvements in the life of specimens with such a deep notch.

Figure 9 summarizes the effect of a single rolling condition on the fatigue resistance of four aluminum alloys. The shaded portion of the bars encompasses the scatter of the results of the number of specimens tested, shown at the left end of the bar, and the "X" is located at the average strength level typical for the group. The strength factors at the right are based on these typical numbers. The pattern of these factors for an alloy exhibits no obvious correlation with other properties of the alloy. One significant indication is that those alloys which were harmed most by notching when unworked received the most benefit by rolling before notching.

Table IV lists fatigue test results from another wrought alloy, 7075-T6. The data show that rolling at 200 lb load increased the fatigue life of unnotched specimens, but additional load was more beneficial. No further increase is noted in going from 1200 to 1800 lb roller load. The fatigue life of the specimen rolled with a 200-lb load prior to notching was approximately tripled, but at 1800 lb, the life of the rolled specimen was 1250 times that of an untreated specimen.

Figure 10 illustrates the scope of work that has been done on commercial casting alloys. All data are from specimens without notches. The data represent a very large range of shot size and peening intensity. The strength improvement at 1 million cycles ranges from 31 to 56 per cent. A rolled specimen stressed at ±24,000 psi developed a life of 3.5 million cycles; for this life this stress is 81 per cent above that of an as-cast surface specimen.

Test Conditions and Environment

Specimen Design and Loading

Table V lists tests which can be directly compared to show possible effects of specimen size, type of loading, and stress ratio. The first section of this table is concerned with specimens without notches. The rotating-bending or reversed-bending tests show the same order of improvement from rolling. Specimens tested axially at 0 and −1 stress ratio show no significant change when rolled. The specimens tested at a stress ratio of +0.5 show an appreciable loss in strength from rollin g

TABLE III.—EFFECT OF VARIOUS ROLLING TREATMENTS ON THE FATIGUE LIFE OF 2014-T6 SPECIMENS NOTCHED AFTER ROLLING AND TESTED AT 30,000 PSI.

Rolling Conditions: Roller Dimensions, in.: Diameter	Contour	Load, lb	Feed, in.	Notch Depth, in.	Life, Cycles	Life Factor, $(R+N)/N$
1⅜-in. Diameter Rotating-Beam Specimens						
None.......	...	...	...	None	350 000	...
1⅜	½	1800	0.021	None	4 000 000	...
None.......	...	...	...	0.020	18 000	...
1⅜.........	½	200	0.021	0.020	200 000	11
1⅜.........	½	1200	0.021	0.020	5 000 000	280
1⅜.........	½	1800	0.021	0.020	6 200 000	340
None.......	...	...	...	0.200	40 000	...
1⅜.........	½	1200	0.021	0.200	90 000	2.2
1⅜.........	½	1800	0.021	0.200	350 000	8.8
1½-in. Diameter Reversed-Bending Specimens						
None.......	...	...	...	None	1 400 000	...
3...........	$\frac{1}{16}$	200	0.008	None	10 000 000	...
None.......	...	...	...	0.020	40 000	...
3...........	$\frac{1}{16}$	200	0.008	0.020	2 200 000	55
3...........	$\frac{1}{16}$	200	0.016	0.020	1 000 000	25
3...........	$\frac{1}{16}$	300	0.004	0.020	9 000 000	225
3...........	$\frac{1}{16}$	600	0.004	0.020	6 000 000	150
3...........	$\frac{1}{16}$	200	0.016	0.030	540 000	...

NOTE.—$(R + N)$ is life of rolled and notched specimens; (N) is life of untreated specimen with notch.

TABLE IV.—EFFECT OF SURFACE ROLLING ON SMOOTH AND NOTCHED FATIGUE RESISTANCE OF 7075-T6 ALUMINUM ALLOY.

Rolling Condition	Notch Depth, in.	Life at 35,000 psi, cycles	Life Factor	Strength at 10^6 Cycles, psi	Strength, per cent
As machined......	None	180 000	1.0	27 500	100
Rolled, 200 lb......	None	2 500 000	14	38 000	138
Rolled, 1200 lb.....	None	15 000 000	83	47 000	171
Rolled, 1800 lb.....	None	15 000 000	83	47 000	171
As machined.......	0.020	8 000	1.0	...	...
Rolled, 200 lb......	0.020	22 000	2.8	...	...
Rolled, 1800 lb.....	0.020	10 000 000	1250	45 000	...

NOTE.—1⅜-in. diameter rotating-beam specimens; rolling with 1⅜-in. diameter by ½-in. radius roller at 0.021-in. feed.

TABLE V.—EFFECT OF TYPE OF LOADING, SPECIMEN SIZE, AND STRESS RATIO ON RESPONSE TO ROLLING FOR 2014-T6 ALLOY.

Type Loading	Specimen Diameter, in.	Stress Ratio	Rolling: Contour Radius, in.	Rolling: Load, lb	Maximum Stress at 10^6 Cycles, psi	Per Cent Change Due to Rolling
Specimens Without Notches						
Rotating bending....	1.375	−1		None	26 000	
			½	200 to 1800[a]	33 000	+27
Reversed bending....	1 500	−1		None	31 000	
			${}^{1}\!/_{16}$	200	37 500	+21
Rotating bending....	0.400	−1		None	34 000	
			½	800	45 000	+32
Axial..............	1.13	−1		None	25 000	
			${}^{1}\!/_{16}$	200	25 000	0
Axial..............	0.300	−1		None	32 000	
			½	480	33 000	+3
Axial..............	0.300	0		None	51 000	
			½	480	50 000	−2
Axial..............	0.300	+0.5		None	65 000	
			½	480	56 000	−14
Specimens with 0.020-in.-Deep Sharp V-Notch						
Rotating bending....	1.375	−1		None	...	
			½	1200	34 000	
Reversed bending....	1.500	−1		None	19 000	
			${}^{1}\!/_{16}$	200	32 500	+71
Rotating bending....	0.400	−1		None	14 000	
			½	800	24 000	+72
Axial..............	1.13	−1		None	9 500	
			${}^{1}\!/_{16}$	200	15 000	+58
Axial..............	0.300	−1		None	7 000	
			½	480	9 000	+29

[a] Range of loads for three specimens. Fatigue results practically identical for all three.

TABLE VI.—EFFECT OF ELEVATED TEMPERATURE ON LIFE OF SURFACE-ROLLED 2014-T6 SPECIMENS TESTED AT 40,000 PSI.

Soak: Temperature, deg, Fahr	Soak: Time, hr	Test Temperature, deg, Fahr	Life Improvement Factor
....		Room	83
....		200	8.7
....		300	1.8
212......	1000	Room	1.2
212......	1000	212	1.1
200......	1	Room	22
300......	1	Room	3.6

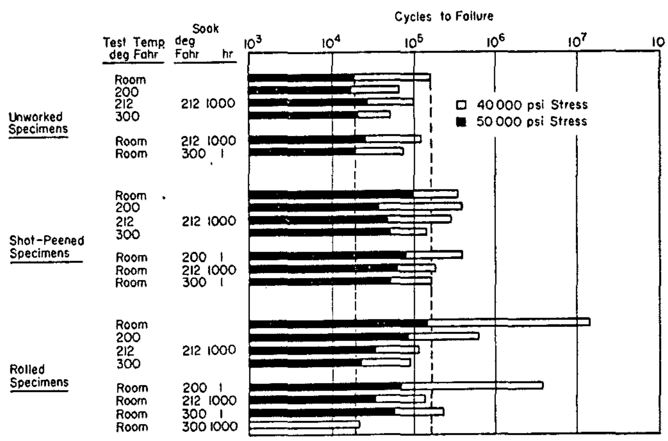


Fig. 11.—Effect of temperature on fatigue life of cold-worked specimens of 2014-T6 alloy.

This loss was verified by several tests of both rolled and unrolled specimens. The maximum stresses at stress ratios of zero and +0.5 are in the plastic range of the material, and one would expect little benefit from cold working, but the loss in strength is surprising and, as yet, unexplained. One possible explanation is the increased surface roughness caused by rolling.

The lower section of Table V shows the various types of notched specimens tested at a stress ratio of −1. The available data do not permit a quantitative comparison to be made of rolling effect alone on the large specimens tested in rotating-bending and reversed-bending. However, the improvements are large, and the absolute values for the rolled and notched specimens in the two situations are quite similar. The large axial specimen showed a somewhat lesser, but still a large, improvement. The level of strength for the notched axial specimens is considerably below those for the bending specimens. This reduction is characteristic of this style of testing (8). Improvement for the small axial specimen was about half that for the larger. Note that the notch depth was kept constant in these tests, not its proportion to the specimen diameter.

These data indicate that surface cold working is not useful unless a gradient is present in the applied stresses. This gradient may be the type that is produced by bending loads or the local type in the neighborhood of a superficial notch. Neither the large nor the small axially loaded specimens showed any gain from rolling, which produced significant changes in smooth bending and notched axial test specimens. Since there was no improvement in axial specimens at −1 stress ratio, it is not surprising that none was noted at higher stress ratios.

Heating After Cold Working

Much of the effect of surface cold working in improving fatigue resistance is attributed to the residual stresses introduced. Since the elastic limit of materials is reduced at elevated temperatures, one would expect that residual stresses will be relaxed at elevated temperatures by proportions depending

TABLE VII.—EFFECT OF PRESTRESSING BEFORE CORROSION ON SUBSEQUENT FATIGUE LIFE.

Surface Treatment	Strength at 10^6 Cycles, per cent of as-machined strength: 2014-T6	2024-T4	7079-T6	Cast C355-T61
None, corroded...	69	83	66	74
Rolled, corroded...	122	117	104	...
Shot peened, corroded...	81	104	...	108

Note.—
1. All specimens of an alloy exposed together, prior to testing, for 1 week by immersion in solution of 5.3 per cent NaCl, 0.3 per cent H_2O_2.
2. Rolled specimens with 3 by ${}^{1}\!/_{16}$-in. roller at 200 lb, 0.008-in. feed.
3. Shot-peened specimens with S-230 cast steel shot to 0.010 A.
4. Specimens 1.5-in. diameter, tested in reversed bending.

TABLE VIII—EFFECT OF ROLLING 2014-T6 SPECIMENS WITH UNFAVORABLE (TENSILE) RESIDUAL STRESSES.

Preloaded	Rolled	Notched	Strength At 10^6 Cycles, psi	Effect of Preload, per cent	Effect of Rolling, per cent
No........	No	No	31 000	...	...
Yes........	No	No	17 000	−45	...
Yes	Yes	No	29 500	...	+73
No........	No	Yes	19 000	...	...
Yes	No	Yes	12 000	−37	...
Yes........	Yes	Yes	26 500	...	+121

Note.—1.5-in. diameter specimens tested in reversed bending. Preload produced a bending (Mc/I) stress of 115,000 psi. Rolled with 3-in. diameter by ${}^{1}\!/_{16}$-in. radius roller at 200 lb, 0.008-in. feed. Notch 0.020-in. deep. All failures on side preloaded in compression.

on the stress level, the temperature, and the time of exposure.

The tests described in Table VI and illustrated in Fig. 11 were conducted on a group of 0.4-in. diameter rotating-bending specimens of 2014–T6 alloy. Some were left untreated, some were shot peened with S-230 shot to 0.016A,[2] and some were rolled with a $1\frac{3}{8}$- by $\frac{1}{2}$-in. roller at 800-lb load and 0.021-in. feed. Tests were run at 40,000 and 50,000 psi at various temperatures, and at room temperature after thermal exposure as indicated.

The lives of the untreated specimens were not greatly affected by the thermal condition imposed. In room-temperature tests, rolling was much more effective than shot peening. In tests at 200 F, the rolled-specimen improvement dropped to approximately 10 per cent of its value at room temperature. When tested at 300 F, the improvement was approximately 2 per cent of its room-temperature value — the effect of rolling had essentially disappeared. Long exposure to 212 F wiped out all significant effects of the rolling. Short exposure to 200 F before testing at room temperature reduced the improvement, but a rolled specimen still had 22 times the life of an unrolled specimen. Short exposure to 300 F further reduced the improvement, but it was still considered significant.

Checking at other temperatures and stress levels and for other alloys is needed before restrictive thermal limits are set. The fact that brief thermal exposure or mechanical overloading can cause plastic action that will reduce the residual stresses set up by earlier cold working is a serious limitation on the use of the methods. The possible future exposure of a machine part to these influences in processing, assembly, installation, or service should be carefully checked before approval of cold-working as a manufacturing process.

Corrosion

Table VII shows how the "notch" effect created by exposure to corrosive environments can be mitigated by cold-working before exposure. The effect of this particular exposure was about the same as that of a 0.020-in.-deep sharp machined notch. In all cases, cold working before exposure gave protection against the reduction in fatigue resistance caused by the corrosion. Rolling led to large improvement; the relatively light shot peening gave less.

Based on visual observation, the apparent attack on unworked and cold worked surfaces were very similar. The observed benefit in fatigue resistance is derived from the residual compressive surface stresses. These surface stresses are also quite effective in increasing resistance to stress corrosion, a mode of failure of certain materials which is only possible in the presence of surface tensile stresses and corrosive environment.

[2] All arc heights are for standard steel Almen test strips.

Unfavorable Residual Stresses

The presence of unfavorable (tensile) residual stresses can reduce the fatigue resistance of metals. Such stresses could be caused by heat treatment, forming or straightening operations, or certain types of machining or grinding. Table VIII summarizes a test designed to simulate this effect and investigate the influence of cold working with such stresses already present. The 2014-T6 specimens were installed in a device in which high static bending loads could be applied. All were loaded in one direction to give a stress (Mc/I) of 115,000 psi. Strain gages placed on one specimen revealed a total strain under load of 2.5 per cent. When the load was removed, the fibers which had received the maximum compressive stress under load were left in a state of tensile residual stress.

The effectiveness of the tensile residual stress in reducing fatigue resistance is shown by the fact that a preloaded smooth specimen showed a 45 per cent loss in strength. A specimen which was preloaded, then notched 0.020 in. deep showed a 37 per cent loss. Each is compared to similar specimens without preload. If the preloaded specimens were subsequently rolled, dramatic improvements were observed. The preloaded, then rolled, specimens, with or without subsequent notching, attained strengths of about 80 per cent of similar specimens without preloading (Fig. 9).

Conclusions

1. Surface cold working can have a large effect on the fatigue resistance of aluminum alloys. The degree of response varies widely, depending on many factors. In certain situations, the fatigue strength of a specimen may be more than doubled.

2. Large specimens without notches, tested in bending at a stress ratio of −1, showed moderate strength improvement from cold working, with little effect of method or intensity of cold working. Similar specimens tested with axial loading derived no significant benefit.

3. The harmful effect of sharp, shallow notches on fatigue resistance can be reduced or cancelled by cold working before notching. Prestressing intensity must be sufficient for the notch depth. Benefits are present in both bending and axial-load tests.

4. All aluminum alloys tested, both wrought and cast, responded significantly to cold working. Relative response varied considerably among the alloys tested.

5. Elevated-temperature exposures which have a small effect on the basic fatigue strength can cause a large reduction in the benefits of cold working.

6. Tensile residual surface stresses can sharply reduce fatigue resistance, while subsequent cold working mitigates this reduction.

7. Aluminum alloy specimens were shot peened as heavily as 0.028A with S-230 shot and 0.013C with S-550 shot. They were rolled to maximum computed ("elastic") contact stresses as high as 860,000 psi. To these limits, there was no indication of reduced fatigue resistance due to excessive intensity.

8. Even though some of the cold working treatments resulted in very rough surfaces, considered unacceptable from an appearance standpoint, fatigue resistance was comparable to other treatments producing smoother surfaces.

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