Effect of Shot Blasting on Strength of Metals

By J. M. LESSELLS* and W. M. MURRAY†

PART II

THE curves for the elastic stages of the tension tests were obtained by the use of Martens Mirror, Huggenberger, and de Forest-Ruge extensometers. These curves are shown in Fig. 4.

In the case of Armco iron, S.A.E. 1045 annealed, S.A.E. X4340, and S.A.E. 9260 there is little or no difference shown by the tension test for the un-shot-blasted or shot-blasted conditions. In the case of S. A. E. 1045 for the heat-treated condition where, due to the heat treatment chosen, the residual stresses are assumed to be high, there are some effects shown by shot blasting. This seems to indicate that the superimposing of a residual compressive stress on the outer layers by shot blasting a section already under residual stress due to heat treatment, results in a lowering of the proportional limit, yield point, and tensile strength. As will be seen later this reduction in tensile strength was not in evidence in the case of shot-blasted spring wire.

The fatigue results obtained on each steel are summarized in Table III and plotted in Fig. 5.

In the case of the annealed S.A.E. 1045, and S.A.E. X4340, there are very definite increases in fatigue life and endurance limits by shot blasting. The increase in endurance limit seems to increase with increase in hardness. The effect of shot blasting the S.A.E. 9260 increases the fatigue life, but makes little or no difference in the endurance limit.

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For the heat treated S.A.E. 1045 it should be noted that the hardness is greater than that which would be generally adopted and the endurance for the un-shot-blasted condition is higher than the normal value. These high hardnesses chosen for the above two steels were selected in order to obtain a range of hardness irrespective of any residual stresses which might result. The presence of these residual stresses may have prevented any change in endurance limit due to shot blasting.

Shot Blasting of Unmachined Surfaces

Shot blasting has been applied successfully to certain automobile and aeroplane engine parts. For a number of years[5] it has been standard practice in this country to shot blast valve springs. Extensive commercial applications for the shot blasting of other springs such as leaf springs have been made by the Eaton Manufacturing Co. Below are given certain results on carbon spring wire. In this work the authors have collaborated with H. H. Clark of that company.

The material tested was domestic wire 0.162 in. in diameter and of the following analysis:

	Per cent
Carbon	0.65
Manganese	0.76
Silicon	0.20
Phosphorus	0.018
Sulfur	0.026

Tension and fatigue tests were made on wire samples for the un-shot-blasted and shot-blasted

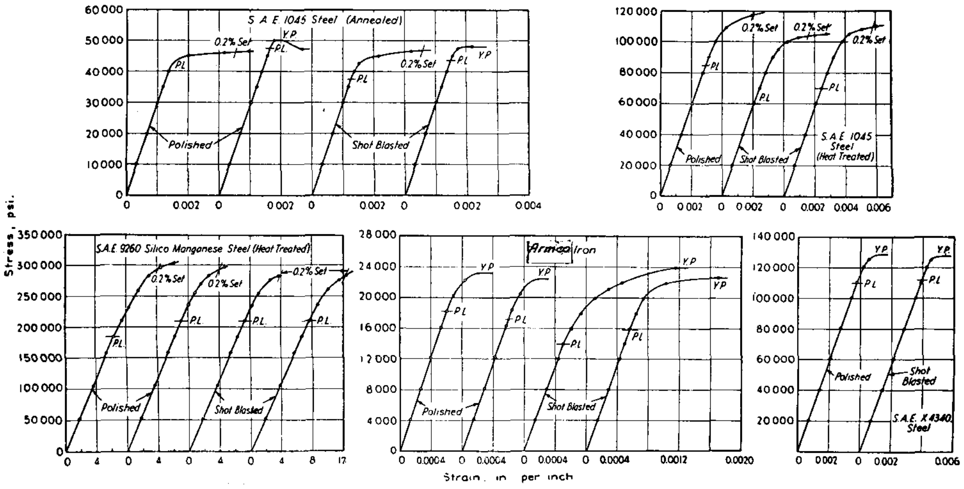

Fig. 4—Tension test diagrams

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PART III

THE increase in fatigue strength due to shot blasting is held to be due to the compressive stress developed in the outer layers. In order to ascertain whether such a conclusion is tenable a brief review will now be made of residual stresses arising from heat treatment and cold work.

It is generally recognized that these residual stresses are of two kinds, namely, microscopic stress and macroscopic stress. Nadai[6] points out that a classification can be made on the basis of whether the elements in which they occur are comparable in size to the crystal grains, hence microscopic in character, or to the size of the stressed body, hence macroscopic. Very little is known at present as regards the microscopic stresses although we do know that stress relieving of hardened and tempered steel gives a different form of tension test diagram although no structural change has taken place.

Quenching and Tempering:

In quenched-and-tempered steels the macroscopic residual stresses have been measured. Heyn[7] was the first to work on this subject. Using quenched cylinders and measuring the change in length after removing successive surface layers he found that the outside was in compressive stress and the center in tension. Some work has been published by one of the authors[8] on cylinders 1½ in. in diameter by 4 in. long of 0.42 per cent carbon and 1.0 per cent carbon steel. The results are shown in Table IV.

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Although the surface stress as recorded above was compressive at the outside, when this was decreased by a modification of the heat treatment the endurance limit was increased even though the tensile strength was decreased. Furthermore, while the 0.42 per cent carbon steel with a Brinell hardness of 578 was in a highly stressed condition the 1 per cent carbon steel with a Brinell hardness of 495 had no appreciable residual stress. This seems to suggest some generalization to the effect that a steel may be heat treated to such a high hardness that an abnormal condition is developed so that its fatigue strength may be less than it would be with a reduced hardness.

Table V—Effect of Tempering on Fatigue Strength

Series	Brinell Hardness Number	Tensile Strength, S, psi.	Endurance Limit, S_e, psi.	Ratio $\frac{S_e}{S} = n$
AA	522	294,200	120,000	0.41
BB	488	282,000	112,000	0.40
CC	433	226,100	98,000	0.43
DD	356	172,900	89,000	0.51
EE	242	148,500	78,000	0.52

Other data[9] are available in the literature on the effect of tempering on the fatigue strength. Moore published data on a 3½ per cent nickel steel (Table V). This was annealed, heated to 1450 F., and oil quenched. The series AA was not drawn, BB was drawn at 400 F., CC at 600 F., DD at 800 F., and EE at 1000 F.

These results indicate that as the tensile strength is decreased by increase in tempering temperature the endurance limit does not decrease as rapidly as evidenced by the increase in ratio n. This increase

Table IV—Effect of Quenching Stresses

Material	Treatment	Brinell Hardness Number	Tensile Strength, S. psi.	Endurance Limit, S_e psi.	Ratio $\frac{S_e}{S} = n$	Surface Compressive Stress, psi.
0.42% C............	Normalized. Heated to 1562 F. and quenched in salt solution. Drawn at 210 F.	578	249,000	81,000	0.325	110,000
0.42% C............	Normalized. Heated to 1435 F. and quenched in salt solution. Drawn at 590 F.	477	215,000	98,000	0.45	30,000
1.0% C.............	Normalized. Heated to 1472 F. and quenched in salt solution. Drawn at 570 F.	495	240,000	112,000	0.46	negligible

Table VI—Effect of Tempering on Fatigue Strength

Tempering Temperature deg. Fahr.	Tensile Strength, S, psi.	Endurance Limit, S_e, psi.	Ratio $\frac{S_e}{S} = n$
900	153,000	72,000	0.47
1000	148,000	74,600	0.50
1100	132.000	74,000	0.56

in the value of n might very well be due to a reduction in residual stress. McAdam[10] published data even more striking on a 3½ per cent nickel steel. The steel was quenched in water from 1450 F. and tempered at 900, 1000, and 1100 F., giving the results shown in Table VI.

These values again show that as the tempering temperature is increased an increase in the ratio n is to be expected. In this case the actual endurance limit is increased. Extensive data have also been published by Gillett.[11, 12] A nickel-chromium-molybdenum steel of analysis 0.41 per cent carbon, 2.49 per cent nickel, 0.79 per cent chromium, 0.76 per cent molybdenum gave the results shown in Table VII.

These results show that the endurance limit and endurance ratio can be increased by a suitable tempering operation.

Fatigue Strength of Cold-Worked Steels

A great amount of experimental data are available on the effect of cold work on the fatigue strength of steels, and since the mechanism of shot blasting is being discussed it seems advisable to review briefly the results which have been made available by various investigators.

Stretching:

Moore and Kommers[13] investigated the endurance limit of a 0.18 per cent carbon steel after different amounts of cold stretching and obtained a considerable increase, while Horger[14] did similar work on a 0.48 per cent carbon steel and also obtained increases.

In the case of stretching it can be assumed that the macroscopic stresses are zero. Nevertheless, an increase in endurance limit was experienced for all cases.

Cold Drawing:

For the case of cold drawing references must be made to the work of Brown.[15]

Gill and Goodacre[16] also published important results on different carbon contents for greater degrees of reduction. Where overdrawing was not in

Table VII—Effect of Tempering on Fatigue Strength

Condition	Brinell Hardness Number	Endurance Limit, psi.
Oil quenched and drawn........	400	100,000
Redrawn	385	106,000
Redrawn and slowly cooled.....	365	112,000

Table VIII—Effect of Cold Stretching on Fatigue Strength

Material	Reduction of Area Due to Cold Stretching, per cent	Tensile Strength, S, psi.	Endurance Limit, S_e, psi.	Ratio, $\frac{S_e}{S} = n$
0.18% C......	1	61.500	28,000	0.45
	8	67,600	35,000	0.52
	17 to 18	73,400	41,000	0.56
0.48% C......	0	88,600	39,800	0.45
	8	111,500	50,000	0.43
	17 to 18	107,000	54,000	0.50

evidence increase in endurance limit by reductions from 25 to 90 per cent were found.

In this process, due to the fact that the outer layers are drawn over the underlying ones, the outer fibers are in a state of tensile stress. These investigators also found that there is a definite limit to be reached in cold drawing beyond which the fatigue strength will decrease although the tensile strength is increased. For the 0.86 per cent carbon steel this point was reached at 82 per cent reduction. A further important point was that the endurance ratio was very low varying from 0.32 to 0.22* but that it could be increased by suitable tempering after cold drawing, provided that the reduction by drawing was less than 60 per cent. Beyond this point no benefits in endurance limit or endurance ratio were obtained by tempering.

Cold Rolling:

Much work has been done on the cold rolling of surfaces. Foppel[18] was the first worker in this field to be followed later by Behrens.[17] Peterson[19] and Horger in this country have since made important contributions to the subject.

Horger[14] reported for a 0.48 per cent carbon steel increases of 24 to 32 per cent in fatigue strength. The depth of the cold-worked material varied from 0.006 to 0.015 in. depending on the normal roller pressure.

In this case the stresses on the outside are compressive.

Shot Blasting:

In the case of shot blasting a high compressive stress is developed in the outer skin. The depth affected by the shot blast is very small, being as previously indicated approximately 0.006 in. on a 1-in. diameter specimen.

Table IX—Effect of Cold Drawing on Fatigue Strength

Material	Reduction of Area Due to Drawing, per cent	Tensile Strength, S. psi.	Endurance Limit, S_e, psi.	Ratio $\frac{S_e}{S} = n$
0.29% C.....	0	72,000	34,500	0.48
	11	86.000	39,000	0.45
	23	98,000	40,700	0.41
	35½	104.000	45,000	0.43

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the maximum force that can be transferred from the acting tool to the section being worked. Therefore, impact consumes a portion of the force that could be utilized for an increased reduction to be performed in a single operation.

The methods being used to decrease impact effects are mainly of two types. One method reduces the speed of the acting tool during the starting period, either directly by the use of direct current motors or indirectly by inserting "soft" members, which yield before the maximum force is developed. The other method is to design the tool in such a manner that the metal itself acts as an impact cushion. For example, in deep drawing (Fig. 23) sharp-cornered tools almost immediately create the maximum metal resistance and the impact effect, while generously rounded off tools permit the metal to move before developing a high flow and impact resistance. As previously discussed, the impact effect is mainly restricted to the region where tools and stock strike each other (Fig. 22). The particles in this contact area suffer the highest impact acceleration, but this acceleration is rapidly reduced as the distance from the contact area increases. The stresses set up in the metal and in the tools are of two types, the plastic or elastic resistance of the metal plus an additional stress proportional to the acceleration. From this feature of any impact effect, the interesting conclusion can be drawn that the stock should be placed in the parts of the dies that are particularly highly stressed, while the less strained part should be the impacting tool.

Regarding the effects produced by the heat developed during working, it should be recalled that the mechanical work consumed is almost entirely converted into heat.[56] This heat comes from two sources, a uniform or volume part originating from the strain within the metal and a surface portion resulting from the friction. The corresponding increase in temperature is determined by the dissipation of the heat mainly due to conduction through the tools and the metal itself. Therefore, the faster the total volume of metal is being worked and the shorter the time the tools remain in contact with the metal after working, the higher will be the increase in temperature of the metal, other factors being equal. This temperature increase can assist the working, as in impact extrusion, or it can cause difficulties, as in the hot-working of a metal with a narrow working temperature range. Apparently little has been done as yet to apply the laws of heat transfer to metal-working problems.

Conclusion

In concluding, may I be permitted to say a few words as to the probable future development of the knowledge of the plastic deformation and rupture of metals. As a science, this branch of metallurgy is most akin to the theory of elasticity. However, the complex theory of elasticity is based on a minimum number of basic assumptions, incorporated in Hooke's law, and on the knowledge of a few properties of the material; i.e., the elastic constants. Other factors, such as the deviations from Hooke's law, or imperfections of elasticity, are of minor importance and do not diminish the tremendous practical usefulness of the theory of elasticity. On the contrary, the plasticity and rupture of metals depend, as discussed, upon numerous fundamental factors and also upon numerous specific metal properties. Therefore, extensive research combining carefully balanced theoretical and experimental work will be necessary to achieve further success. Unfortunately, rather sensitive, complex and expensive experimental equipment is required for this work, and as a consequence the progress in this particular field of metallurgy will be rather slow.

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Residual Stress Versus Cold Working

In the light of these results it is possible to summarize the effects of these various processes. This is done in Table X.

Table X—Summary of the Effect of Various Proocesses

Condition	Type of Surface Stress	Depth of Cold Working, in.	Effect on Endurance Limit
Quenched and tempered	Compressive	......	Decrease
Stretched	None	Entire surface	Increase
Cold drawn	Tensile	......	Increase
Cold rolled	Compressive	0.006 to 0.015	Increase
Shot blasted	Compressive	0.006	Increase

As to a probable cause for the effect of such processes as cold drawing or cold rolling on the endurance limit there are several schools of thought. Foppel[20] believes that the increase is due to deformation of the surface and consequent hardening, while Thum[21] believes it is due to compressive stresses in the outer layers. It is somewhat difficult to accept the viewpoint of Thum since, as previously discussed, in a quenched-and-tempered steel high residual compressive stresses may exist if the hardness is carried beyond a certain limit. Under such stress condition the endurance limit value may be considerably lowered. In no case examined were such stresses found to be favorable. On the other hand in the case of drawn rod or wire the residual stresses at the outside are tensile. Nevertheless, provided no overdrawing exists, increase in fatigue strength can be expected. Obviously these occurrences which are well supported by experimental evidence would be reversed if stress were the chief governing factor, since we would expect a compressive stress on the outside to be beneficial in fatigue, and conversely a tensile strength on the outside to be detrimental.

Consideration of these facts leads to the conclusion that the shot-blasting process produces a cold working of the outer surface which is the main contributing factor to increase in fatigue strength. Nevertheless, the results may also be influenced by the stress distribution and the increase in fatigue strength may be due to a combination of cold work and residual stress.

Discussion

In the light of the experimental data given in this paper and the results of previous work by Zimmerli, it is seen that under certain conditions considerable increase in fatigue life and endurance limits can be expected from shot blasting. This is true for all the steels tested but in the case of those steels which have high residual stress due to quenching and insufficient tempering this increase on endurance limit may not be in evidence. Evidently when the high compressive stresses on the outside due to quenching have compressive stresses due to shot blasting superimposed there is created a condition in which the cold working of the surface has little or no effect. At least the available experimental evidence seems to point that way.

Previous research has indicated that a smooth and highly polished surface is necessary for high fatigue strength. This now requires some modification because in the case of shot blasting the surfaces are slightly roughened.

Conclusions

The conclusions which can be drawn from this work are as follows:

1. Considerable increase in fatigue life and endurance limits of steels can under certain conditions be obtained by shot blasting the surface. By inference similar advantages may be gained for metals other than steel.

2. The increase in fatigue life and endurance limits seems to be due to a cold working of the outer surface although the resulting compressive stress may be beneficial.

3. There does not appear to be any advantage as regards endurance limits in shot blasting surfaces where high residual stresses due to quenching and insufficient drawing are present.

4. The beneficial effects can be removed by annealing but annealing at low temperatures, provided this is not sufficiently high, is beneficial as regards fatigue life for shot-blasted surfaces.

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