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## Summary

The weight of material removed upon erosion of 1045 steel samples which had been subjected to different heat treatments was measured. Two types of erodant particles were used: glass beads and crushed glass. The results show that there is no correlation between hardness and erosion resistance.

It was found that the erosion rate depends strongly on the shape of erodant particles. Weight loss in erosion with crushed glass was an order of magnitude higher that that with glass beads.

For erosion with glass beads, the heat treatment and the resulting microstructure have a profound effect on the erosion resistance, while it has little or no effect in the case of erosion with crushed glass. One is, thus, led to the conclusion that different mechanisms of material removal are involved in these two cases.

This is supported by the surface morphologies obtained in those two cases as observed by scanning electron microscopy (SEM). The morphology of an annealed 1045 steel eroded with crushed glass indicates that the main mechanism of material removal is cutting, while the surface morphology of the steel eroded with glass beads shows that deformation-induced fracture of surface layers is the dominant wear mechanism.


## Introduction

In a recent study (ref. 1) into the effect of heat treatment on the erosion behavior of 6061 aluminum alloy, it was found that the erosion resistance can be significantly increased by means of a proper heat treatment (such as solution treatment). It was also found that, as opposed to results reported for pure metals (ref. 2) where the erosion resistance had been shown to be linearly proportional to hardness, such a correlation between hardness and erosion resistance does not necessarily hold for alloys. Thus, precipitation hardening, which results in increased hardness, brings about a slight decrease in the erosion resistance.

It was of interest to extend the study of the effect of heat treatment and microstructure on the erosion behavior to other alloy systems. Because of the wide variety of heat treatments that can be applied to steel and the many types of microstructures resulting from those treatments, it provides a very useful system for studying the relation between microstructure and erosion resistance. The fact that steel is the most common construction material made this study even more attractive. This study is a part of a general program aimed at gaining a better understanding of the effects of various material properties on erosion behavior in order to find means for reducing erosive wear.

## Materials

The samples were cylinders 25 millimeters in diameter and 13 millimeters long made out of the same stock of 1045 steel (0.43–0.50% C; 0.6–0.9% Mn; maximum 0.04% P; maximum 0.05% S). They were subjected to the following heat treatments:

1. Annealing performed by heating to 790° C, furnace cooling to 650° C and cooling to room temperature in still air.
2. Spheroidizing performed by first annealing and then keeping at 705° C for 24 hours.
3. Normalizing performed by heating to 900° C and cooling in still air.
4. Quenching performed in water after austenitizing at 855° C.
5. Tempering, performed on quenched samples by keeping at 120°, 315°, 540°, or 685° C for 1 hour.
6. Austempering performed by first austenitizing at 855° C and quenching in a salt bath kept at either 400° or 510° C.

## Experimental Procedure

Specimens were eroded in an industrial sand-blasting apparatus. Two types of erodant particles were used: glass beads, with an average diameter of 15 micrometers, and crushed glass (fig. 1).

Argon was used as the driving gas in order to minimize corrosion effects. The distance between nozzle and specimen was 13 millimeters. The erosion tests were made at normal incidence and lasted 10 minutes for erosion with glass beads and 5 minutes for erosion with crushed glass. The nozzle diameter was 1.18 mm.

Although the values of some experimental parameters such as particle speed and flow rate were not measured, reproducible weight-loss results were obtained with a variation not exceeding $\pm 3$ percent.

The Rockwell A test was used for hardness measurements after polishing the samples. Etching of the samples for metallographic purposes was done with nital.

## Results and Discussion

Microstructures resulting from the various heat treatments are shown in figure 2. The weight losses resulting from erosion with the two types of erodant particles, as well as the phases present in each case and the hardness values, are listed in table I. In figure 3 the erosion resistance, defined as the reciprocal of the weight loss during the erosion test (ref. 2), is presented versus the hardness of the various samples. It is clear from that figure that, as in the case of 6061 aluminum alloy (ref. 1), there is hardly any correlation between the erosion resistance of a given material and its hardness. This is different from the observations reported by Finnie, et al., for pure metals (ref. 2) where the erosion resistance was found to be linearly proportional to hardness.

The most conspicuous feature of the results is revealed on comparing the results for the two types of erodant particles. First, an order of magnitude higher weight loss values occur on erosion with crushed glass as compared with those obtained for erosion with glass beads. Moreover, while for erosion with glass beads the heat treatment has a very strong effect on the erosion resistance, little or no such effect is observed for erosion by crushed glass. These results clearly indicate that different mechanisms are involved in the two cases. Many studies have been conducted with spherical particles (ref. 3 to 7). Since sharp particles appear to generate results different from that observed with spherical particles, a more careful examination of shape effects seems warranted.

Examination by scanning electron microscopy of the surfaces resulting from erosion with these two types of erodant particles leads to the same conclusion. The SEM micrographs presented in figure 4 show that the surface morphologies are quite different. It is seen from these micrographs that for erosion with crushed glass the major mechanism of material removal is cutting, whereas for erosion with glass beads deformation-induced fracture of surface layers is the dominant wear mechanism.

## Conclusions

The conclusions of this study are

1. There is no correlation between the erosion resistance of a given material and its hardness.

2. Erosion rates depend strongly on the shape of the erodant particles. Thus, weight loss resulting from erosion with sharp glass particles is an order of magnitude higher than that resulting from erosion with spherical glass particles.

3. While heat treatment and the resulting microstructure have a profound effect on the resistance to erosion by glass beads, they have little or no effect in the case of erosion by crushed glass. This implies that different mechanisms of material removal are involved in these two cases.

4. Examination by means of scanning electron microscope of the surface morphologies resulting from erosion with the two types of erodant particles indicates that, for erosion with crushed glass the main mechanism of material removal is cutting and for erosion with glass beads it is deformation-induced fracture of surface layers.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 27, 1980,
506-53.

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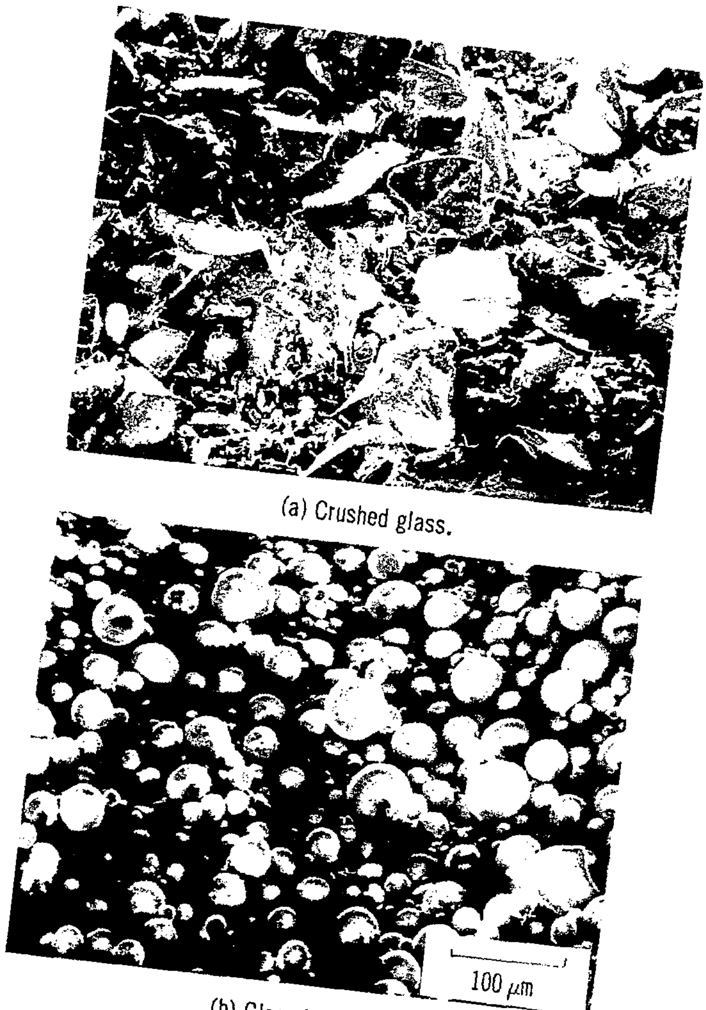
TABLE I. - MICROSTRUCTURE, HARDNESS, AND EROSION OF 1045 STEEL

SUBJECTED TO VARIOUS HEAT TREATMENTS

| Heat treatment | Phases present | Rockwell A hardness | Weight loss after erosion for 5 minutes with crushed glass, g | Weight loss after erosion for 10 minutes with glass beads, g |
|---|---|---|---|---|
| Annealed | Ferrite and coarse pearlite | 51 | 0.121 | 0.0242 |
| Spheroidized | Cementite in ferrite matrix | 47 | 0.119 | 0.0296 |
| Normalized | Ferrite and fine pearlite | 57 | 0.121 | 0.0206 |
| Water quenched | Martensite in retained austenite matrix | 68 | 0.117 | 0.0044 |
| Water quenched and tempered at 120° C | Transition carbide in austenite matrix | 68 | 0.115 | 0.0041 |
| Water quenched and tempered at 315° C | Tempered and untempered martensite | 67 | 0.120 | 0.0179 |
| Water quenched and tempered at 540° C | Cementite in ferrite matrix | 65 | 0.120 | 0.0200 |
| Water quenched and tempered at 685° C | Cementite in ferrite matrix | 60 | 0.116 | 0.0248 |
| Austenitized and austempered at 400° C | Lower bainite | 61 | 0.113 | 0.0197 |
| Austenitized and austempered at 510° C | Upper bainite | 58 | 0.119 | 0.0139 |



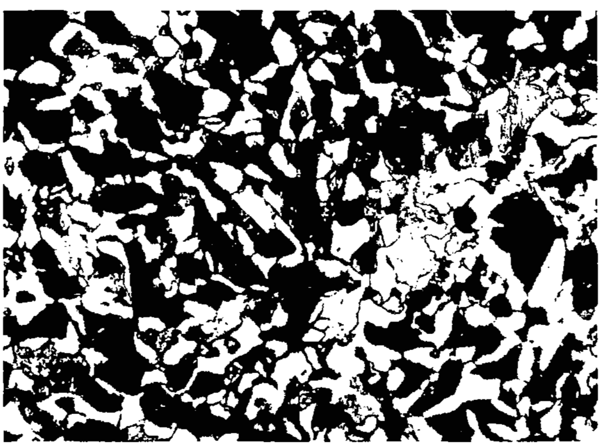

(a) Crushed glass.

(b) Glass beads.

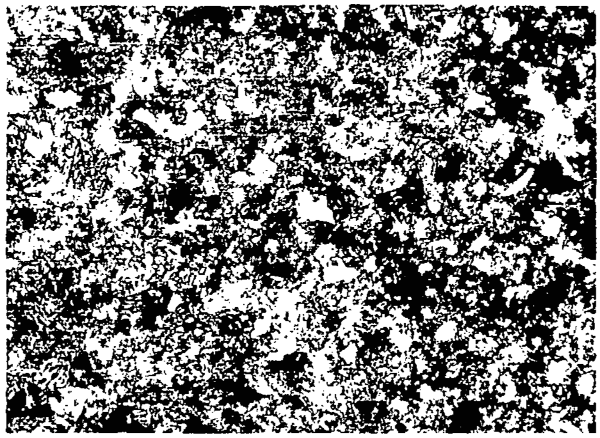
Figure 1. - Erodant particles used in this study.

(a) Annealed.

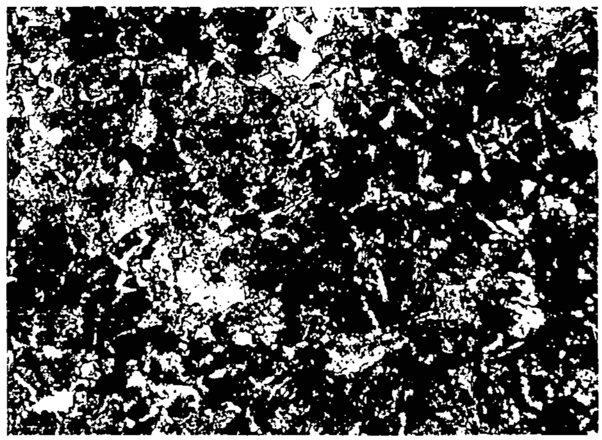
(b) Spheroidized.



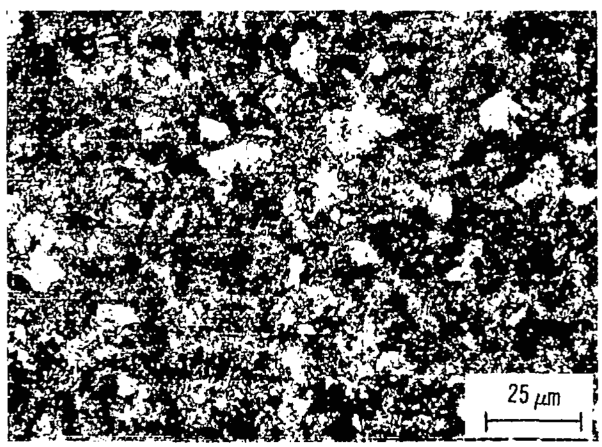
(c) Normalized.



(d) Water quenched.

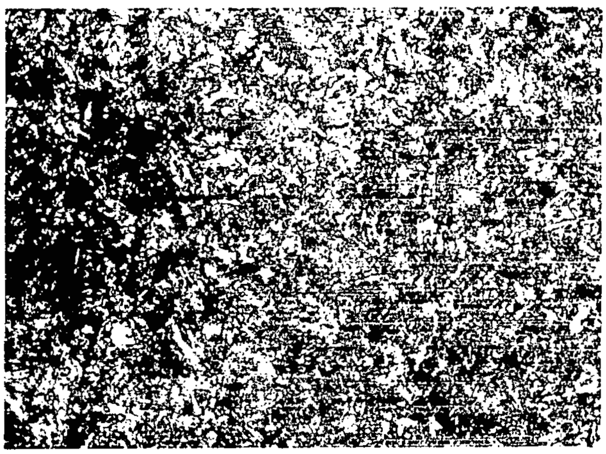


(e) Quenched and tempered at 120° C.

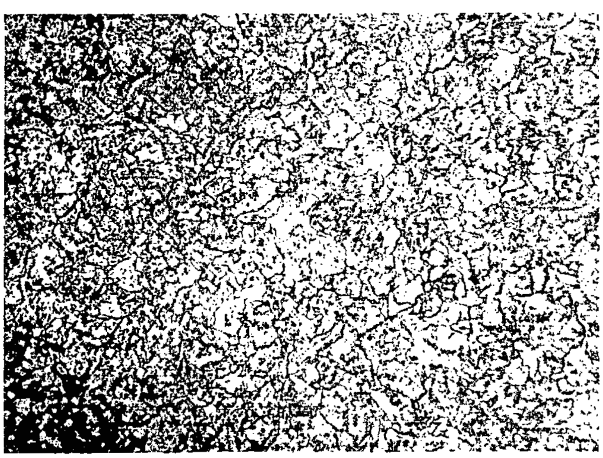



(f) Quenched and tempered at 315° C.

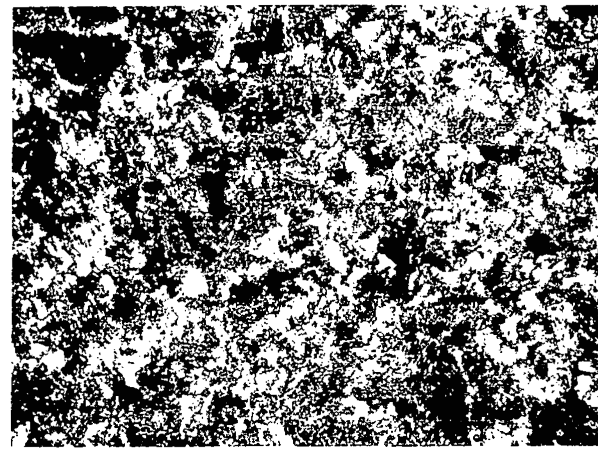
Figure 2. - Microstructure of 1045 steel.



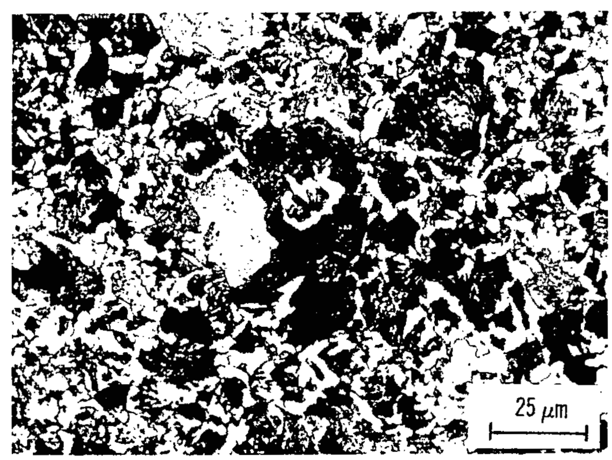
(g) Quenched and tempered at 540° C.



(h) Quenched and tempered at 685° C.



(i) Austempered at 400° C.




(j) Austempered at 510° C.

Figure 2. - Concluded.

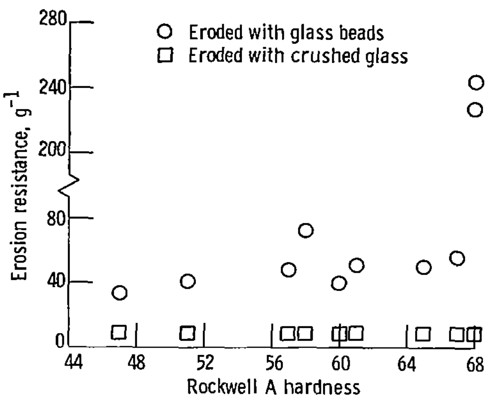
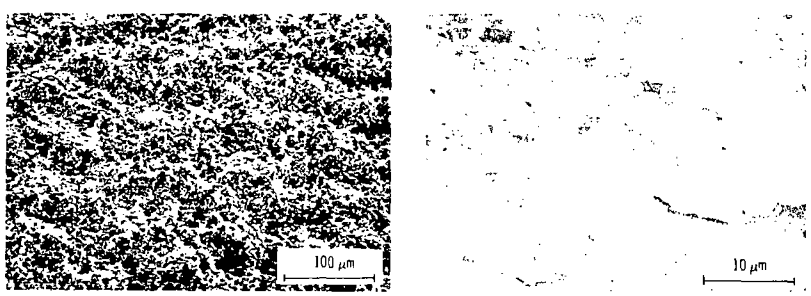
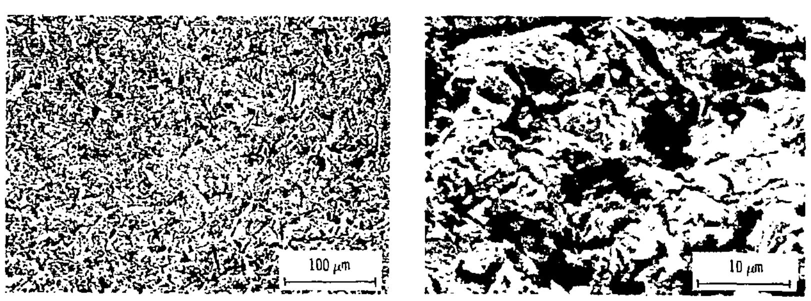



Figure 3. - Erosion resistance versus hardness for 1045 steel after various heat treatments.




(a) Glass beads.




(b) Crushed glass.

Figure 4. - SEM micrographs of the surface of annealed 1045 steel after erosion with glass beads or crushed glass.

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16. Abstract

Erosion tests were conducted on 1045 steel samples which had been subjected to different heat treatments. The weight of material removed upon erosion with glass beads and crushed glass was measured. The data shown that there is no correlation between hardness and erosion resistance. The erosion rate was strongly dependent on the shape of erodant particles, being an order of magnitude higher for erosion with crushed glass than with glass beads. Heat treatment had a profound effect on the erosion resistance when the erodant particles were glass beads but little or no effect when the particles were crushed glass. It is thus concluded that different mechanisms of material removal are involved with these two erodants. This conclusion is supported by in the surface morphology of annealed 1045 steel samples which had been eroded by these two types of erodant particles. SEM micrographs of the eroded surfaces show that for erosion with crushed glass the main mechanism of material removal is cutting whereas for erosion with glass beads it is deformation-induced fracture of surface layers.

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