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ADIABATIC SHEARING IN FERROUS ALLOYS.(U)  
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Adiabatic Shearing in Ferrous Alloys.

Final Report.

Prepared by

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FOREWORD

This program was begun three years ago with the intent of adding to and clarifying the information available on the phenomenon of adiabatic plastic deformation in ferrous alloys. One of the major goals of this study was to be an elucidation of the role of deformation per se in the phenomenon over and above the fact that dynamic localized deformation provided the temperatures that permitted austenitization and rapid quenching. This goal was never reached during the contract period, principally because it became clear that a more thorough knowledge of the behavior of a number of steels and ferrous alloys during dynamic deformation was requisite to a comparative study of the effects of rapid local heating with and without accompanying deformation.

This work is, however, still being carried out at no cost to the sponsor and the current state of this activity is discussed below.

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### EXPERIMENTAL APPROACH

The dynamic deformation studies were carried out using a modified compressed air gun at Drexel University. The flat-nosed projectiles were made of hardened tool steel approximately 0.6 inches in diameter and weighing about 0.25 lb. For the most part the projectiles were "stepped". In other words, the actual penetration attempt of the plate targets was made by a short cylindrical flat-nosed step at the front of the projectile. This step gave the relatively heavy projectile a better chance of penetrating the target at the relatively low velocities that could be generated by the air gun. It also limited the penetration to the height of the step or less.

The targets were 1/4 inch to 5/16 inch plates, cut either from plate material of that thickness or removed from 1 inch rounds, depending on availability. Preliminary tests showed that for the materials studied there is no significant orientation effect relative to the direction of working of the target material.

A number of ferrous alloys were studied, many only cursorily. These include AISI 1018, 1040, 1075 plain carbon steels, O2 tool steel, AISI 8620, 4140 and 4340 low alloy steels, 440C stainless steel, A286, 304 stainless steel, several precipitation hardening stainless steel and others. The bulk of the studies, however, were with the plain carbon and low alloy steels.

## PROGRAM AREAS

During the period of the program a number of aspects of the adiabatic plastic deformation of ferrous alloys was examined. Some were examined cursorily; others in some depth. Although initially planned to examine a more narrow aspect of the phenomenon, the influence of deformation during heating as discussed above, the lack of sufficient conclusive information on the behavior of such materials constrained the program to a rather broad brush study characterizing material behavior and pointing to particular areas where more in-depth study is required. The following topics were examined during the period of support:

1. Effect of heat treatment, i.e., microstructural and strength level on the tendency to form transformed shear bands.
2. Influence of strain rate on transformed shear band hardness.
3. Influence of target hardness on the hardness of the transformed shear bands.
4. Transformed shear band hardness level.
5. Influence of carbon content on the microhardness of transformed shear bands.
6. Uniformity of hardness along and across transformed shear bands.
7. For a given composition, the influence of heat treatment.
8. Transformed shear band "propagation".
9. Influence of deformation during heating on the resulting structure and properties of rapidly heated ferrous alloys, i.e., the comparison of the results of laser or electron beam heating with those of adiabatic plastic deformation.
10. Possible compositional gradients in transformed shear bands.
11. Microstructural homogeneity of transformed bands.
12. Effect of composition, heat treatment and stress state on plug formation resulting from projectile impact.

## RESULTS AND CONCLUSIONS

The results of the studies in program areas 1-8 are given and discussed in considerable detail in the two publications cited for the program to date. These results will therefore only be summarized here. They are as follows:

1. In most ferritic steels, transformed adiabatic shear bands are formed if conditions of dynamic deformation are sufficiently severe, i.e., the rate and magnitude of the deformation are sufficiently great. These bands are normally preceded by deformed shear bands.
2. In quenched and tempered AISI 1040 steel, the hardness of the observed transformed bands are independent of the velocity of impact and target hardness.
3. In a series of plain carbon steels, the observed transformed band hardness was found to be considerably greater than that obtainable in the same steel by conventional austenitization and quenching techniques and was linearly related to the carbon content.
4. The extreme hardness of the transformed bands can be explained in terms of the additive effects of hardening of the lattice by supersaturated carbon on quenching and of hardening resulting from the extreme fine grain size in the bands. The structure appears to be a recovered, highly-dislocated martensite. The grain diameters are in the range of fractions of a micrometer.
5. Hardness along the length of the transformed band is constant, indicating minimal effects after austenitization.

6. Microhardness profiles of deformed shear bands indicate that the gradients in work hardening resulting from strain concentration in bands are overwhelmed by temperature gradients during adiabatic shear deformation.

7. Heat affected zones of lower hardness are found surrounding the transformed shear bands when the target microstructure has inadequate thermal stability.

8. The coarser the second phase (carbide, generally) microstructure, the more difficult it is to form transformed bands. This probably is the result of the increased structural stability of coarse structures at high temperature.

9. Increasing yield strength tends to promote band formation; however, since this is normally correlated with a decreasing rate of work hardening when the yield strength increase is accomplished in a given alloy through microstructural changes, it is not clear which is the major contributing factor.

As indicated in the forward, no work was done on item 9 of the program during the period of the contract. Through the cooperation of Dr. E. M. Brainen of the United Technologies Research Center, however, this phase of the program is still being studied. Eight different steels or ferrous alloys for which there are data on the effects of adiabatic shear on their properties and microstructure were sent to United Technologies to be given high speed, high intensity thermal treatments. The alloys are the following:

1. 1040 steel - Annealed.
2. 1040 steel - Q + Temp. - 1 hr. - 800°F.
3. 1040 steel - Q + Temp. 1 hr. - 1100°F.
4. 4340 steel - Annealed.
5. 1075 steel - Annealed.
6. 440-C stainless steel - Q + Temp. - 700°C ( $R_C$ 32)
7. Custom 455 stainless steel - Aged 1100°F - 4 hrs. ( $R_C$ 36)
8. A286 - Aged - 732°C - 16 hrs. ( $R_C$ 36)

The thermal treatments have just been carried out but the details are unknown to me at present. These should be forthcoming shortly and the samples made available for metallographic and other examination. Comparison can then be made with the adiabatically sheared specimens.

As a result of some concern over reports in the Russian literature indicating a change in composition in regions of rapid intense heating it was decided to examine several of the materials where transformed adiabatic shear bands had formed to establish whether any detectable differences could be found between the bands and surrounding matrix material. Wavelength dispersive x-ray analysis of three different steel was made under subcontract of this program by Structure Probe, Inc. of West Chester, Pa. The steels examined were AISI 1040, 4340, and 1075. The advantage of the wave length dispersive analysis of these samples is that it is capable of analyzing for lighter elements such as carbon than is the energy dispersive method.

A series of analyses were taken transverse to the shear bands at 5 $\mu$ m intervals starting and finishing with matrix material. The elements investigated were C, Mn, Si in AISI 1040 and 1075 steels and C, Cr, Mn, Mo and

Ni in AISI 4340 steel. In all cases, although there were some apparently random fluctuations in local composition, no difference in level of alloying element between the transformed band and the matrix was found for any of the elements in any of the steels studied. Although these results were expected, this put to rest any suggestions of possible compositional variations between the shear bands and the target matrix material.

Another area of major effort was the development of techniques for revealing in greater detail the microstructure and its possible heterogeneity in transformed shear bands. It is well known that the transformed bands in carbon and low alloy steels etch only slightly in a nital etch and appear white or structureless while the matrix etches in a conventional manner. For this reason the bands are frequently referred to as "white bands". Extensive examination of the bands in a variety of materials showed the bands to possess a substructure which differed depending on the microstructure of the matrix. The substructure is revealed by the nital etch more by changes in the contour of the previously polished surface of the white bands than by any coloration or shading. This is discussed briefly in the publications cited. Prior investigations using electron microscopic and x-ray techniques have reported different crystallographic structures in the hard, transformed bands. Some report BCC structures, some BCT. Some report evidence of retained austenite; others find no trace of austenite. For these reasons a better knowledge of the microstructure is desirable.

A variety of stain etches were examined. The best results with carbon and low alloy steels were obtained with a solution of potassium metabisulfite at a concentration of 3 gm. per 100 ml. of distilled water. For the

stainless steels, small additions of hydrochloric acid were required for effective etching action.

The effect is distinctly shown in Figure 1. In this 0.40 carbon steel in the annealed condition the matrix microstructure consists of an approximately 50-50 mixture of ferrite and pearlite. When the temperature rises above the eutectoid temperature, the proeutectoid ferrite is unaffected while the pearlite is converted to high carbon austenite. The temperature is not high enough or the time long enough to permit full austenitization. The rapid quench that occurs on cessation of adiabatic plastic deformation converts the deformed austenite to high carbon martensite but does not alter the deformed ferrite. Etching with nital leaves the ferrite and the as-quenched martensite relatively untouched so that they both appear white after etching. The metabisulfite etch on the other hand stains the as-quenched martensite a purplish-brown color without coloring the ferrite. This reveals that the transformed band consists of alternating layers of highly elongated ferrite and martensite regions. Thus the band is quite inhomogeneous so that it is not surprising that previous reports on the band structure are conflicting or confusing.

When this etch is applied to the transformed shear bands found in AISI 1075 steel, the band also appears to contain white regions although they have no connection with any white regions in this hypereutectoid steel. It is our opinion that these are regions of retained austenite although further study is required to establish this with certainty.

A serendipitous result from these studies has been insight into the factors controlling the geometry of the plug ejected or partially ejected from the plate target as a result of impact by flatnosed projectiles. Normally, if the shearing becomes sufficiently localized, a roughly cylindrical plug with

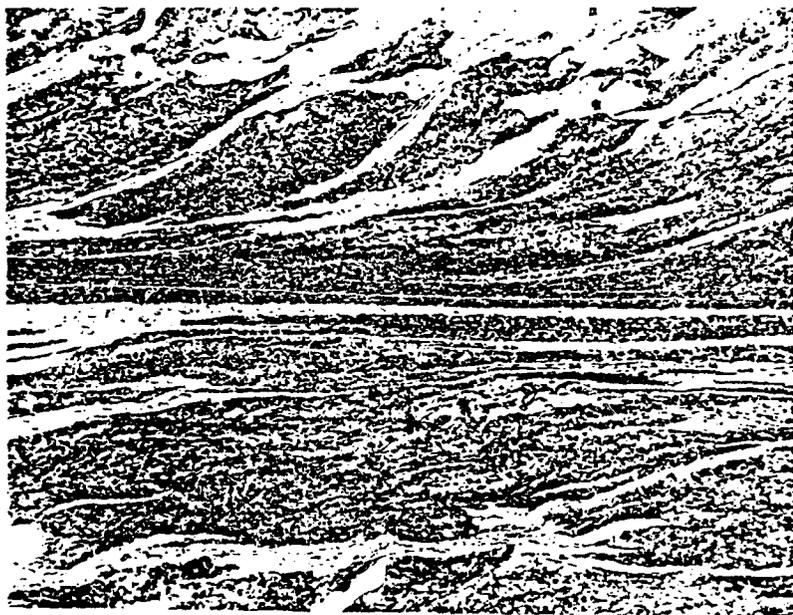


Figure 1. Transformed adiabatic shear band in AISI 1040 steel, annealed to produce a ferrite-pearlite matrix (band is horizontal). Etched in potassium metabisulfite solution. (500X)

radial dimensions about that of the projectile or the step on the nose of the projectile is found. In the case of 1075, 440C and 329 it was found that under some conditions of heat treatment a conical plug formed after the blunt step on the projectile had penetrated a small fraction of the target thickness. The base of this conical plug was approximately the same size as the step on the indenter. It was observed that the materials and conditions that produced conical plug formation also led to fracture of the target material during the penetration process. In other words, the conical plug formed when the target was heat treated to be relatively brittle. When these same target steel compositions were heat treated to reduce their hardness and increase their ductility, a conventional cylindrical plug was formed on impact.

It was hypothesized that the change in nature of the plug was primarily the result of a change in the ability of the target material to flow laterally under the compressive action of the impacting indenter. Normally a ductile target acts as though it were an infinite plate and little or no radial flow is permitted. When the target is more brittle indentation begins, followed by cracking of the target. Upon cracking, the lateral constraint on the radial flow of the target material under the indenter is removed or reduced substantially. This allows the material under the indenter to behave as a dynamically compressed cylinder. As a result of indenter-target interface friction a conical dead zone forms in the target immediately under the indenter surface. As in any compression test there is a high concentration of shear deformation in the zone adjacent to the zone of dead metal. When the deformation takes place at a high rate, this shearing is adiabatic and the cone separates from the remainder of the fracturing target.

This view is supported by the results of several additional experiments in which the 1 inch diameter plate targets were pressed into a 1 inch diameter hole in a larger 3 inch diameter hardened steel plate. This gives considerable lateral support, reducing but not eliminating the tendency for target cracking when these materials are in the more brittle condition. On impact such laterally supported targets tend to crack but at a later stage. Conical plug formation is eliminated and a cylindrical-type plug begins to form. Complete ejection does not occur because the whole plug formation process is interrupted by the delayed cracking of the target.

### SUMMARY

The results of this program cover a number of different aspects of the adiabatic shearing phenomenon in projectile impact. A major portion of the results are described and discussed in the two papers or reports cited. Neither as yet is easily obtainable. The initial aim of the program, to establish the rate of the deformation accompanying the heating in adiabatic deformation, has not been accomplished but is still being investigated. The other aspects of this rather broad brush study described herein provide the beginnings for more detailed and comprehensive studies than were possible during the period of support for this program. With respect to further publications of the information generated during this program, it is expected that at least three additional papers will be prepared as soon as time permits.

PAPERS OR REPORTS OF WORK DURING GRANT

"Material Factors in Adiabatic Shearing and the Implementation for Analysis"  
Report to the Army Research Office for Distribution at the TICP-P-TRI Meeting  
in Australia, May 10, 1979.

"Material Factors in Adiabatic Shearing" at Int. Conf. on the Metallurgical  
Effects of High Strain Rate Deformation and Fabrication, Albuquerque, New  
Mexico, June 1980 (to be published).

STUDENTS SUPPORTED DURING WORK OR DEGREES GRANTED

None

OTHER TECHNICAL PERSONNEL

Dr. C. V. Shastry

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20. Abstract (Continued)

undeformed target hardness. Wavelength dispersive x-ray analysis was made transverse to the shear bands to establish whether or not alloy element concentration differences could be found between the matrix and the band. None were found. A stain etching technique was developed which demonstrates the inhomogeneous nature of the shear bands in many steels. A study was also made of differences in configuration of plugs generated on the target by projectile impact. Studies show a major effect of lateral constraint by the target on plug shape.