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Discussion

F. W. Boulger.[6] This article was read with great interest particularly because the first leaded free-cutting steels were made and tested at Battelle in 1936. At that time no effort was made to investigate the mechanism by which lead improved machinability. The authors' careful study presents considerable evidence indicating that lead acts as an internal lubricant which lowers tool-chip interface temperatures.

Although they do not emphasize the point, the authors mention that sulphide inclusions also function as internal lubricants. Therefore, it is a little surprising to find that sulphur was less effective at high speeds. Perhaps the failure to find benefits from the higher sulphur contents of steels Nos. 6 and 8 compared to steels Nos. 5 and 7 was influenced by the order in which they were tested. Fig. 8 indicates that test cuts were made on both of the higher sulphur steels before the lower sulphur steels were machined. Sometimes, the performance of a specimen in a machining test is influenced by the effect of the preceding sample on a cutting tool. It is conceivable that the practice of cutting the higher sulphur steels first left some "lubricant" on the tool and improved the performance of the lower sulphur steels tested subsequently. We have encountered such effects of "heredity" in constant-pressure tests and in radioactive tool wear tests. For this reason, and as a matter of policy, it would be helpful if the authors would say whether they made more than two measurements in their tests and give estimates of the range in replicate measurements of "u," "F," t/t_c, and $\bar{\theta}_t$. Without this information it is difficult to evaluate the significance of the data.

Because the ductility and Charpy values of the leaded samples were particularly good, it would be desirable to know whether the compositions listed in Table 1 are for the bars tested or represent averages for entire heats.

The last sentence of the section on Lubrication Requirements is intriguing. Do the authors have any evidence that the effect of cold work on machining properties depends on the original hardness of the steel? It has been established reasonably well that certain amounts of cold work improve the machining properties of some materials. In the case of steels, one might expect the effect to vary with the amount of cold work, the composition of the steel, and the prior heat-treatment.

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E. S. Nachtman.[7] The importance of metal removal methods in our economy cannot be over emphasized. Techniques for improving the quality of the machined product with respect to surface finish and dimensional accuracy as well as those for accelerating productivity of the metal removal process are of extreme importance. The discusser would like to comment on just a few points brought out in this paper.

The importance of a built-up edge in protecting the tool so as to give better tool life has long been recognized. However, the built-up edge results in an inferior surface finish. The addition of lead to steel makes possible excellent tool life at speeds where the built-up edge does not persist so that excellent surface finishes are obtainable. As has been pointed out, however, tool wear does not always occur on the tool edge; it may occur in different areas of the tool. Where wear is initiated depends upon a number of factors. Investigation of the factors responsible for wear location would be profitable to all of us concerned with the machining of steel.

A second important concept discussed in the paper is that dealing with the relationship between additions to steel which improve the cutting characteristics of the steel and externally applied cutting fluids. Further investigation of this relationship should prove interesting.

I believe that this paper will stimulate some new approaches directed toward improving the efficiency of metal removal processes.

Authors' Closure

As Mr. Boulger states, it appears that the chief role of the lead particles in a leaded steel is to act as an internal lubricant which decreases the tendency for the chip to adhere to the face of the tool. This is consistent with the observation that a thin layer of lead deposited on a steel surface significantly decreases the coefficient of sliding friction observed when a second steel specimen slides over the coated surface.

While the subject of this paper concerns lead rather than sulphur, the authors did mention the commonly held view that sulphur in the form of manganese sulphide also acts as an internal lubricant. However, since writing this paper, the authors have performed a simple friction experiment in which manganese sulphide was introduced as a lubricant between steel surfaces. It was found that the character of the manganese sulphide was not that of a lubricant, but instead caused a marked increase in the coefficient of friction over the value for dry surfaces. The authors should, therefore, like to take this opportunity to put forth the view that the role of sulphur in a free-machining steel is not that of a lubricant but just the reverse, tending to provide more points of stress concentration in the steel and promoting

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rather than lessening the tendency for a built-up edge to form. This should not, however, be taken to mean that the presence of sulphur is detrimental to machining, for the tendency of an increased sulphur content according to the new view is to improve finish at low cutting speeds and to improve tool life at high cutting speeds. Details of this matter are beyond the scope of this paper and will be presented in a later paper with supporting data.

To answer Mr. Boulger's question concerning the properties of Table 1, they are averages for the heat of steel from which all bars were taken.

For each machining operation there appears to be an optimum workpiece hardness both with regard to surface finish and tool life. If the workpiece hardness is beyond the optimum then additional cold woık will lead to poorer results and vice versa. In the case of very soft low-carbon steels it appears impossible to get the metal too hard from the standpoint of either surface finish or tool life.

We agree with Mr. Nachtman that a built-up edge can sometimes protect a tool from wear and extend tool life although this view is not shared by all workers in this field. It appears that the protection offered by the built-up edge is of most importance at intermediate cutting speeds where crater formation is usually not excessive.