The author wishes to thank Prof. M. C. Shaw and his associates for their interest in this paper. Thanks are due also for the information regarding the work of Dr. Masami Masuko who seems to have followed the same direction in developing further the metal-cutting theory. We, here, were unaware of this work and are now obtaining a translation of Dr. Masuko’s paper so that it may be compared with the recent research of this laboratory.

Starting with the over-all impression of the discussion, we can see that the discussers missed a very important point, namely, that the developments presented in the paper are based on an analysis confirmed by experimental evidence and not on mere assumptions. For instance, under item number 1 of their discussion the discussers say that the author made an assumption about the size of the natural sharpness rounding relative to the magnitude of the uncut chip thickness. No such assumption was made. Instead, the natural sharpness radius was measured by the author and its magnitude in inches stated, permitting direct comparison with the magnitude of the uncut chip thickness. Thus it can be seen that there was no need of any assumption regarding the magnitude of natural sharpness rounding because its magnitude was already known from the author’s measurements. Regarding Fig. 7 and other illustrations it should be mentioned here that the magnitude of the sharpness radii shown in these diagrams was increased for the sake of clarity of illustration.

More specifically, with regard to the size of the natural sharpness rounding (as presented in the paper), it may be found by measurement that the natural sharpness radius is of a magnitude between 0.0002 and 0.0006 in. The lower values of this range usually occur on tools with a higher rake angle (such as +20 deg) and values of the order of 0.0006 in. may occur in the range of negative rake angles. These higher natural values of sharpness radius can be artificially altered to smaller ones by employing such techniques as fine polishing or lapping of the tool face and flank. This may be done for the sake of experiment and the author agrees that such a value as 0.0002 in. can thus be obtained on tools of low rake angle. However, it should be borne in mind that this will be an artificially obtained situation which takes one away from the ordinary conditions of a usual cutting operation.

It is interesting to note that the discussers seem to approve an artificial decrease of the sharpness radius (apparently in an attempt to make it very small and insignificant as compared with $t_1$) but an increase of the sharpness radius for experimentation the discussers proclaim immediately as “poor practice.” The author wishes simply to state here that either increasing or decreasing the natural value of the sharpness radius are equally useful and sound techniques for research on the ploughing process.
Actually, the decreased and increased values of the sharpness radius are two branches of one range of controlled sharpness and there is no reason whatsoever to accept one side of the range and reject the other side of the range for experimentation.

Now let us consider what might cause the discussers to be inclined to such a one-sided preference. As early authors began development of the present theory of metal cutting, certain simplifying assumptions were made, as is usually the case when starting a study of a complex problem. Among these initial simplifications was one about the size and effect of the sharpness radius being small and insignificant compared to the dimensions of the cutting mechanism. Since that time probably every one who raised the question about the significance of the sharpness rounding to the cutting process has heard the phrase “small and insignificant.” This is not surprising, because there was practically nothing known about this very point of the cutting edge. Unfortunately, for many years no study was undertaken to confirm or replace this simplifying assumption made by the early investigators. Thus this initial assumption has, with the years, become a customary way of thinking.

Backed by experimental evidence, the developments presented by the author in this paper break the customary way of thinking about the significance of the sharpness rounding to the cutting process.

Now, let us look at the statement “small and insignificant!” in the light of research presented in the paper. First of all, “small!” was replaced by the results of measurements. The sharpness rounding has been assessed quantitatively and it can be seen that its magnitude is not very great as compared with \( t_i \) or other dimensions of the metal-cutting mechanism. However, how about its “insignificance”? We can see again from the experimental results presented in the paper that the force due to ploughing is significant. Its value may attain hundreds of pounds, equaling in magnitude the other forces of the metal cutting process, in the range of smaller values of \( t_i \). Thus we have arrived at the picture of a comparatively small dimension of the cutting edge with a significant force on it. Is this a controversial result? The answer is that this is not the final picture of what has been found. At this stage the author would like to give a preview of the findings, which happens because of the engagement of the cutting edge in the cut. This wear usually produces a slight increase in the initial sharpness rounding of the cutting edge, so that the edge actually cuts with a slightly larger rounding than that which initially resulted from grinding. Usually, however, this increase of the sharpness rounding is small and does not change the picture very much.

Another factor of greater significance is the presence of a small built-up edge which is still present under conditions which are usually termed as “cutting without the built-up edge.” When cutting steel at speeds as high as 600 fpm, or even higher, this small built-up edge was observed under the microscope. The occurrence of even a small built-up edge increases the effective sharpness radius significantly and thus the ploughing effect and ploughing force. As a matter of fact, the observed development of the ploughing force with increasing \( t_i \), as shown in Fig. 9 in the paper, has been found to be largely due to the development of this small built-up edge with increasing \( t_i \). These are a few of the further steps made since Part I of the paper was written. It appears at this stage that the whole study of the ploughing process is intimately connected with the study of the behavior of the built-up edge. The study of the built-up edge should be extended to include not only the large built-up edge occurring at lower cutting speeds, where it may be observed with the naked eye, but also in the region of higher speeds, where it can be observed only through a microscope.

Summarizing, we can see that the size of the natural sharpness rounding itself is comparatively small (as demonstrated in the paper by the results of its measurement), but its effect upon the cutting forces is significant, mainly due to the fact that the effective sharpness radius is increased by the presence of a small built-up edge. The size of the effective sharpness radius, which includes the effect of the small built-up edge, depends only slightly on the cutting speed (in the region of higher cutting speeds) and depends more on the initial chip thickness \( t_i \), up to a certain value of \( t_i \). Finally, the magnitude of the effective sharpness radius depends also on the sharpness radius of the cutting edge itself. This may be expressed by the formula \( r = r + \Delta r \) (given in the paper) where \( \Delta r \) is the effect of the built-up edge. The magnitude of \( \Delta r \) is affected greatly by the cutting speed in the region of low cutting speeds. This effect almost fades out in the region of the higher cutting speeds where only a small built-up edge occurs and where \( \Delta r \) depends more on \( t_i \) in the region of development of the ploughing force. Finally, it may be said that as soon as the small built-up edge is taken into consideration there will be practically no region of cutting conditions under which a trace of a built-up edge cannot be found. This means that cutting with a built-up edge seems to be the usual condition, at least when cutting steel.

Let us return now to the objections of the discussers regarding points 2 and 3 of the discussion, that is, regarding the force \( Q \) being proportional to \( t_i \) and the coefficient of friction on the chip-tool interface being constant with \( t_i \).

Actually, the discussers’ experiment (involving artificial reduction of the length of contact of the chip on the tool face), instead of tending to disprove these two points, tends to confirm the validity of the author’s entire approach. If, as the discussers assume, there is no ploughing force or ploughing effect acting at the cutting edge, then the cutting force and chip friction will be determined entirely by the simple contact between the chip and the flat tool face only. One cannot conceive how, in such a symmetrical situation, artificially reducing the contact length on the tool face could have any effect on the direction of the single resultant force generated by the pressure of the chip against the flat tool face—and thus any effect on the observed coefficient of friction. However, the discussers (as have other people before them), observed a change in the magnitude and direction of the resultant force on the tool when they artificially decreased the chip-tool contact length. This can only mean, then, that the picture of the entire resultant force being associated with the contact on the flat tool face is too simple; that there must be a second force system contributing to the resultant force in addition to the tool face forces—namely, a force system at the cutting edge—a ploughing force. Then, artificially decreasing the contact length on the tool face will change the relative magnitude of these two force systems—that on the tool face and that at the cutting edge—thus changing the observed magnitude and direction of the over-all resultant force, even though the direction of the tool face force and the ploughing force do not change.

This change in magnitude and direction of the resultant force—i.e., change in cutting force and apparent coefficient of friction—predictable only when two force systems are postulated, is exactly what the discussers observed. Thus, this simple experiment confirms the existence of a ploughing force and is consistent with the picture of a tool face force \( Q \) which is proportional to \( t_i \), but constant in direction (coefficient of tool face friction independent of \( t_i \)).