# Effect of Reduction Ratio on the Machinability of a Medium Carbon Microalloyed Steel

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**Even though the effect of reduction ratio on mechanical properties and fatigue has been studied, no work on its effect on machinability has been reported. In this work, billets of microalloyed steel were rolled to various diameter bars yielding a range of reduction ratios. Machinability was then evaluated by the turning test, the plunge test, and the drill test. Results show no deleterious effects of lower reduction ratio on machinability. In some aspects, machinability decreases with increasing reduction ratio. The cause can be traced to slightly increased as-rolled hardness of bars with higher reduction ratios.**

Keywords
machinability, microalloyed, reduction ratio

## 1. Introduction

REDUCTION ratio is the amount of reduction that a final product has gone through from the as-cast stage and is generally expressed as the ratio of the cross-sectional area of the as-cast ingot, bloom, or billet and the cross-sectional area of the final bar or rod. Reduction ratio has been known to affect both the internal structure as well as properties of the product. There have been several studies on the effect of reduction ratio on centerline defect and porosity (Ref 1-4) and numerous studies on the effect on mechanical properties (Ref 5-11). The effect of reduction ratio on fatigue has also received considerable attention (Ref 12-17). A recent summary and work on the effect of reduction ratio is contained in Ref 18.

Surprisingly, although internal structure, tensile and impact properties, and fatigue have received the attention they deserve, machinability has received scant attention in the literature. Yet, almost all components are machined to a certain extent to produce the final finished part, and the machining step of the production process, in most cases, is the costliest step in production. The objective of this work was, therefore, to study the effect of reduction ratio on machinability; to the best of the author's knowledge, this is the first reported study of its kind.

At the outset, two points must be clarified. First, this work is an empirical study of the effect of reduction ratio. In other words, no attempt was made to vary reduction ratio while controlling its concomitant effects. Therefore, this study represents the "total" effect of reduction ratio.

Second, reduction ratio can be varied in two ways: (a) by varying the final product diameter starting from the same as-cast size, or (b) by varying the as-cast size and processing to the same final diameter. This work has used the first method exclusively. Because it is not clear if the two methods of varying reduction ratio have similar metallurgical effects, the results of this study may not be applicable to a situation where reduction ratio is varied by the second method.

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## 2. Experimental Procedures

### 2.1 *Machinability*

Most, if not all, components go through considerable machining after casting or forging for manufacture of the final part. Contribution of the machining operation to the total cost of manufacture is often 50 to 60%. The machining properties are, therefore, of great interest in the application of materials.

Machinability, however, is not a unique material property that can be clearly defined and measured, such as tensile strength. It is a system property depending on dynamic interactions among the workpiece material, tool material, lubricant, and machining conditions. Thus, there are many sets of operations and criteria for machinability, and the same material may have a different machining response when a different set of machining operation is used. To deal with this complex situation, the approach adopted in the literature has been to address several criteria to assess machinability (Ref 19). Improved machinability is, thus, characterized by one or more of the following: (1) increased tool life obtainable, (2) a higher rate of material removal, (3) lower energy or forces, (4) better surface finish, and (5) easier chip removability.

In this work, the approach of multiple testing using different machining operations and different machinability criteria was used to fully characterize machining properties.

The first test was a continuous turning test using a LeBlond Makino CNC lathe. In all tests, the tool material (HSS T-15 grade), depth of cut (2.5 mm or 0.10 in.), and feed rate (0.127 mm/rev or 0.005 ipr) were kept constant, and catastrophic tool failure was used as the criterion of tool life. The cutting speed to give a tool life of 20 min ($V_{20}$) or full Taylor tool life curves were used to assess machinability.

The plunge test was developed at Inland Steel to obtain information on the form machining operation. A parting tool was used to plunge into a bar being rotated at a constant surface speed by the CNC lathe. The tool (M2), feed rate (0.063 mm/rev or 0.0025 ipr), and depth of cut (2.5 mm or 0.10 in.) were kept constant. Tool forces in two directions—the cutting force and the thrust force—were measured and used to assess machinability. Tool life until catastrophic tool failure can also be used as a criterion. In this investigation, the plunge tests were run at one speed of 0.51 m/s (100 sfm).

**Table 1 Chemical composition of the steel**

| Element | Composition, wt% |
|---|---|
| C | 0.46 |
| Mn | 0.82 |
| P | 0.016 |
| S | 0.027 |
| Si | 0.24 |
| Cr | 0.11 |
| Mo | 0.02 |
| Ni | 0.06 |
| Cu | 0.14 |
| V | 0.14 |
| N | 0.12 |

**Table 2 Bar diameters, reduction ratios, and bar hardnesses**

| Bar diameter mm | Bar diameter in. | Reduction ratio(a) | Hardness (HRC) |
|---|---|---|---|
| 76 | 3 | 6.9 | 22 |
| 74.7 | 2.94 | 7.2 | 22 |
| 63.5 | 2.5 | 10.0 | 23 |
| 51 | 2 | 15.6 | 24 |
| 38 | 1.5 | 27.7 | 23 |
| 28.6 | 1.125 | 49.3 | 26 |

(a) Starting from as-cast size of 178 mm × 178 mm (7 in. × 7 in.)

Because drilling is one of the most important and often rate-controlling machining operations during manufacturing, a special drill test, developed at Inland, was used to study this behavior. The details of this test are given elsewhere (Ref 20); only the salient features are mentioned here. A multiple spindle drill press with infinitely variable feed rates and equipped with a dynamometer to measure the drill force and drill torque was used. In this work, a feed rate of 0.2032 mm/rev (0.008 ipr) and a speed of 1000 rpm were used with a constant 9.5-mm (3/8-in.) diam. drill, 25-mm (1-in.) hole depth, and –M7 (HSS) drill material. To avoid variability from manufacturer's drill points, all drills were ground in-house to a specially designed point before testing. Four drills were used to drill six holes each. The average drill force and drill torque were then used to assess drillability.

Chip disposability is an important part of machinability. Hence chip form was evaluated qualitatively. Finally, chip thicknesses were measured in order to better understand the machining process.

### 2.2 *Materials*

The steel used for this investigation was a continuously cast, vanadium bearing, medium carbon microalloyed steel (10V45) with nominal 551 MPa (80 ksi) yield strength. Table 1 lists the chemical composition of the steel. Mechanical properties and microstructure of the steel as well as detailed metallographic study of the chips were published earlier (Ref 21) and are not repeated here. As-cast billets of 178 mm × 178 mm (7 in. × 7 in.) cross section were rolled to various diameter bars to yield varying reduction ratios. Table 2 lists the bar diameters, reduction ratios, and bar hardnesses.

All bars were of a ferritic pearlitic microstructure with the ferritic grain size decreasing and pearlite volume fraction increasing with smaller diameter bars.

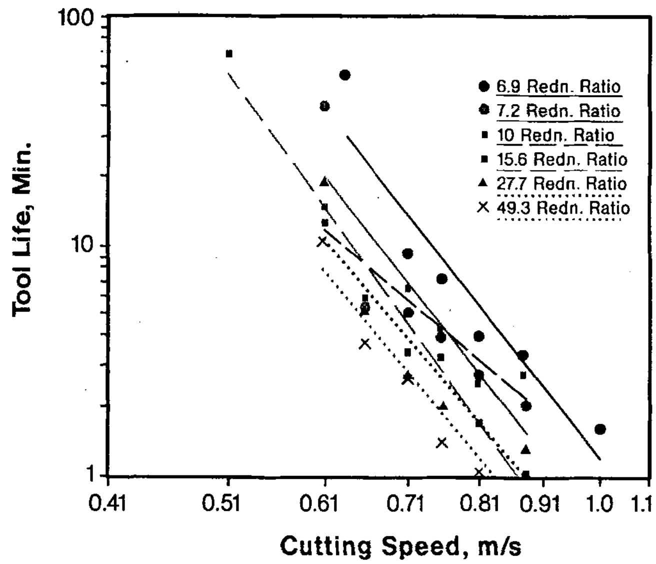


**Fig. 1** Effect of reduction ratio on tool life in the turning test

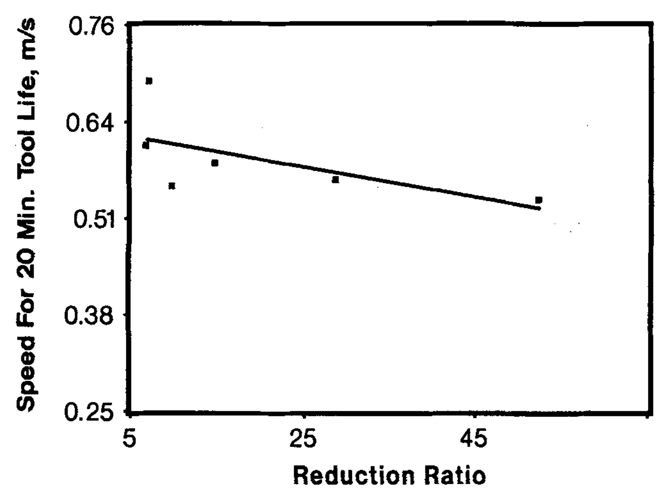


**Fig. 2** Effect of reduction ratio on $V_{20}$ in the turning test

## 3. Results

### 3.1 *Turning Test*

Figure 1 shows Taylor tool life vs. cutting speed curves for steels of varying reduction ratios (product diameters). Although there is some overlap, based on the commonly used guideline of a 10:1 difference in tool life, there is a significant difference between steels with the highest (49.3) and the lowest (6.9) reduction ratios. Furthermore, there is a general trend of improving machinability with lower reduction ratios, as shown

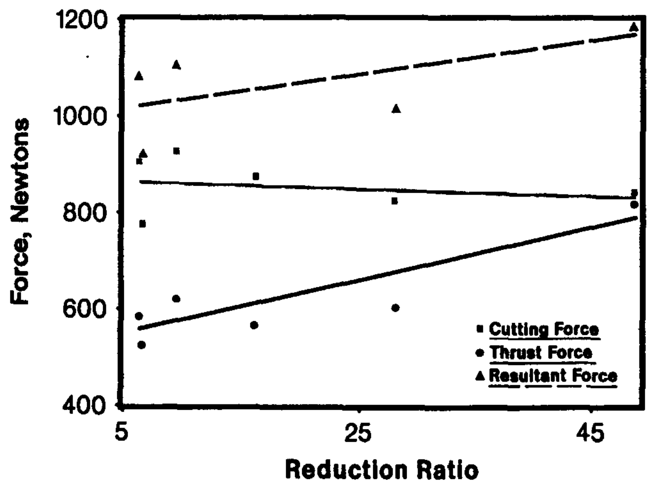


**Fig. 3** Effect of reduction ratio on machining forces in the plunge test

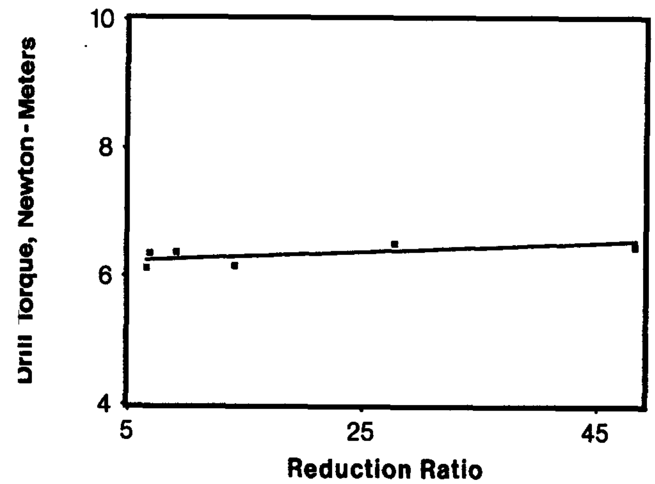


**Fig. 5** Effect of reduction ratio on drill torque in the drilling test

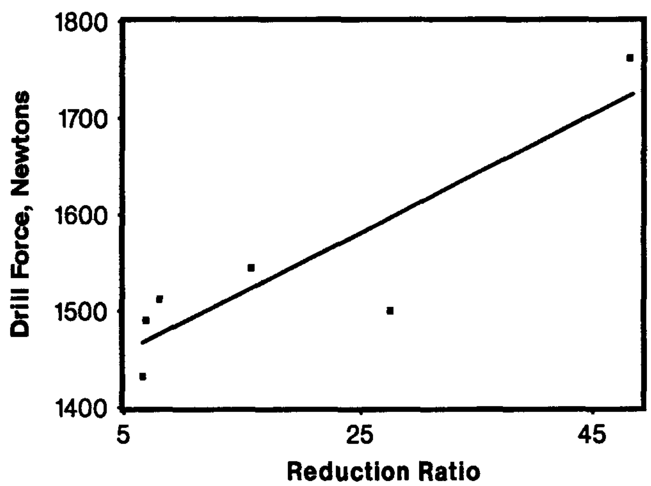


**Fig. 4** Effect of reduction ratio on drill force in the drilling test

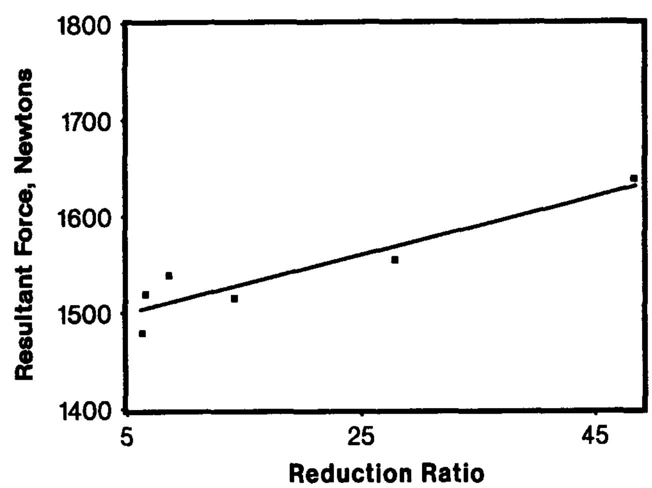


**Fig. 6** Effect of reduction ratio on resultant force in the drilling test

**Table 3 Plunge test results**

| Bar diameter mm | Bar diameter in. | Reduction ratio | Cutting force, N | Thrust force, N | Resultant force, N | Tool life, s |
|---|---|---|---|---|---|---|
| 76 | 3 | 6.9 | 904 | 584 | 1076 | 136 |
| 74.7 | 2.94 | 7.2 | 763 | 516 | 922 | 68 |
| 63.5 | 2.5 | 10 | 919 | 611 | 1104 | 113 |
| 51 | 2 | 15.6 | 871 | 571 | 1042 | 68 |
| 38 | 1.5 | 27.7 | 818 | 599 | 1015 | 45 |
| 28.6 | 1.125 | 49.3 | 840 | 840 | 1188 | 23 |

in Fig. 2, where the speed for a 20 minute tool life, $V_{20}$, is plotted as a function of reduction ratio.

### 3.2 *Plunge Test*

Table 3 gives the plunge test results. Included are the measured cutting and thrust forces and tool life for catastrophic tool failure. Also included is the calculated resultant force based on the formula:

$$F_R^2 = F_c^2 + F_T^2$$

where $F_R$ is resultant force, $F_c$ is cutting force, and $F_T$ is thrust force.

The results, plotted as a function of reduction ratio in Fig. 3, show that there is no significant correlation established between reduction ratio and the cutting force results in the plunge test. However, thrust force increases with increasing reduction

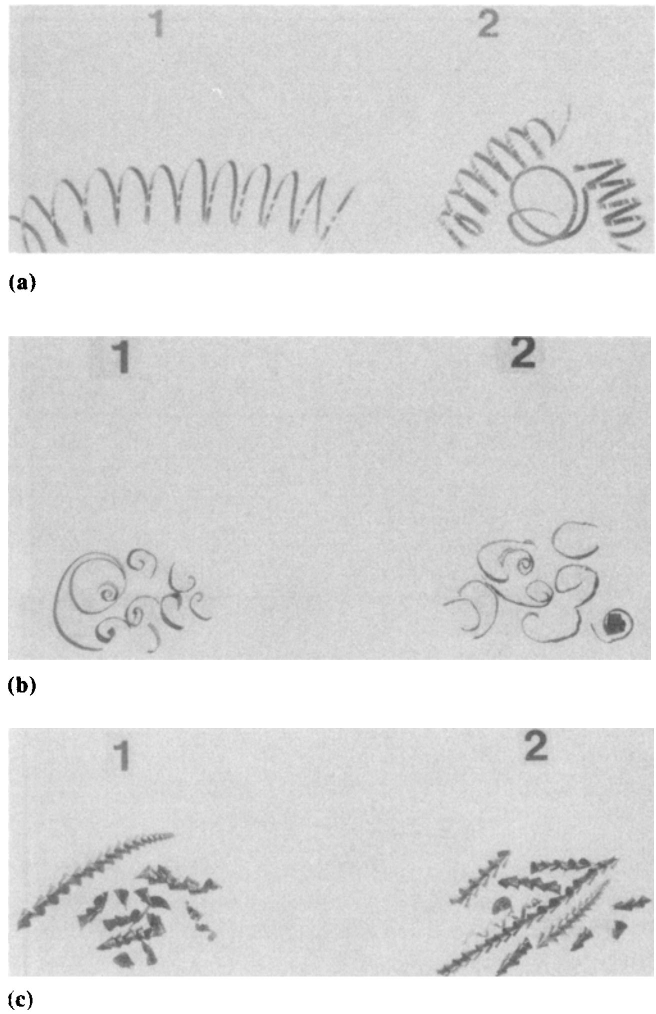


**Fig. 7** Chip morphology in the (a) turning test, (b) plunge test, and (c) drill test for (1) reduction ratio 27 and (2) reduction ratio 10

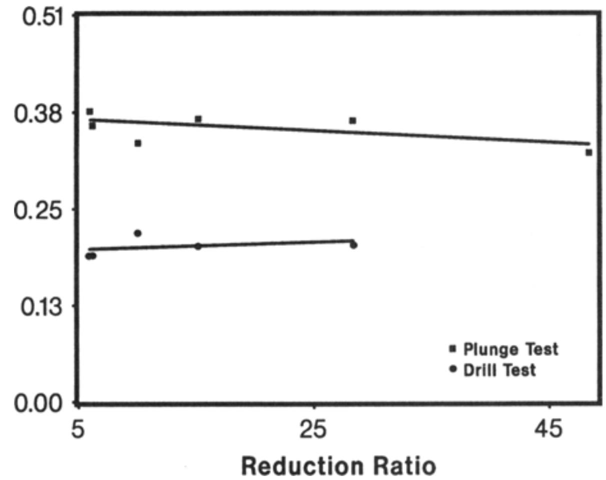


**Fig. 8** Effect of reduction ratio on chip thickness in the plunge and drilling test

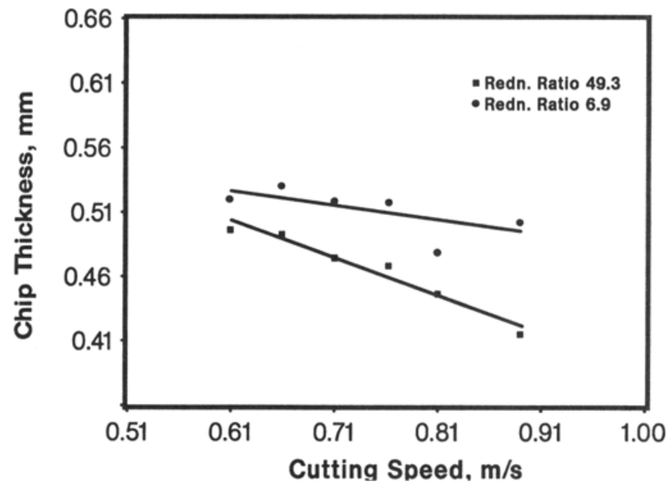


**Fig. 9** Effect of reduction ratio on chip thickness in the turning test

ratio. As a result, there is a similar but small effect of reduction ratio on the calculated resultant force. There also appears to be a decrease in tool life with increasing reduction ratio.

### 3.3 *Drill Test*

Figures 4, 5, and 6 show the drill test results; drill force, drill torque, and calculated resultant force, respectively, were plotted as a function of reduction ratio. Whereas there is no significant effect on drill torque, drill force and the calculated resultant force increase with increasing reduction ratio.

### 3.4 *Chip Morphology and Disposability*

In tests carried out in this investigation, the cutting tools did not have a chip breaker or chip curler in their design. However, in most industrial cutting operations, tools with chip breakers are used. Nonetheless, chip morphology in all tests was observed because it still indicates chip disposability (ease of chip removal) and, hence, ease of the machining operation. Figure 7 shows representative chip samples from the turning test, plunge test, and drill test. No significant differences are observed in the chip shape, indicating similar chip disposability characteristics.

### 3.5 *Chip Thickness*

Chip thicknesses were measured in all the tests because they provide valuable information on chip formation. Figure 8 shows chip thickness as a function of reduction ratio for the plunge and drill tests; Fig. 9 shows the results in the turning test. These results show no significant variation in chip thickness with reduction ratio in the plunge and drill tests. However, in the turning test, there is a small difference in the chip thickness between the steel with the highest reduction ratio and the one with the lowest reduction ratio.

## 4. Discussion

The most significant result of this investigation is that machinability is not adversely affected by lower reduction ratios.

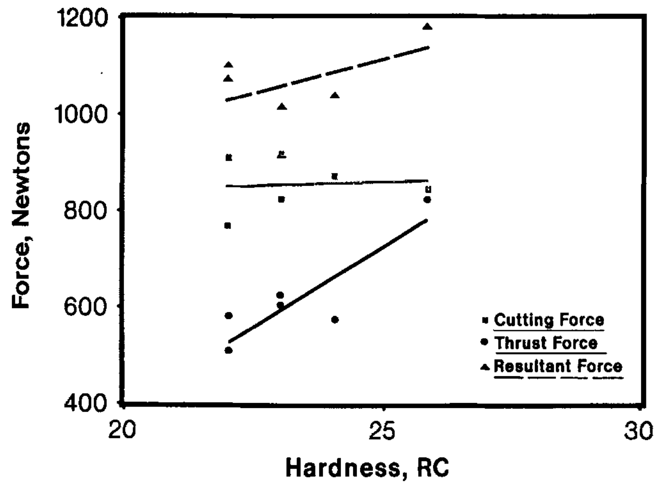


**Fig. 10** Effect of hardness on machining forces in the plunge test

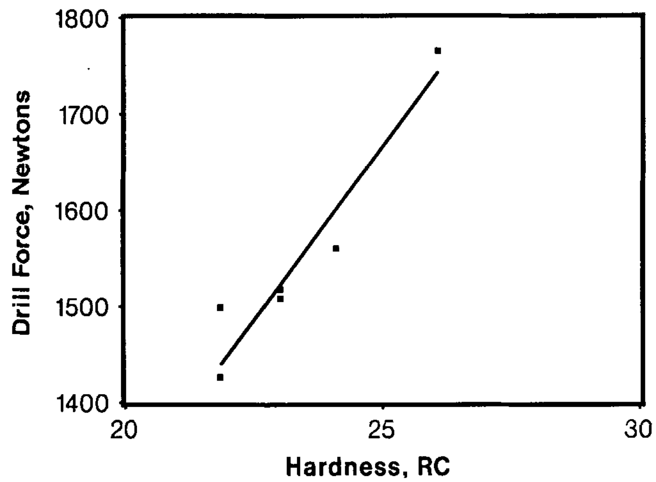


**Fig. 12** Effect of hardness on drill force

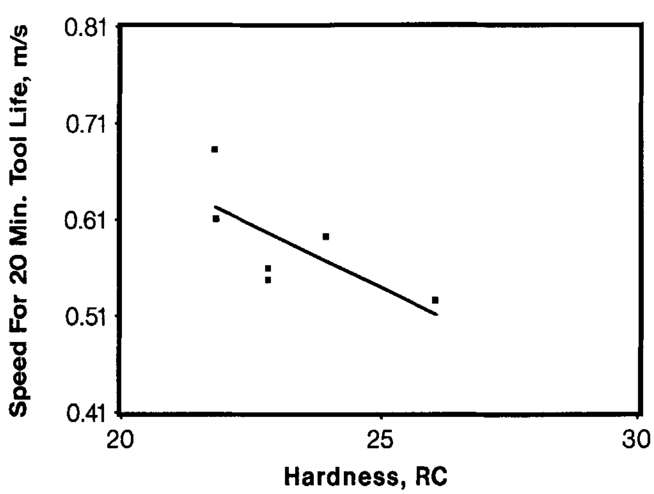


**Fig. 11** Effect of hardness on $V_{20}$ in the turning test

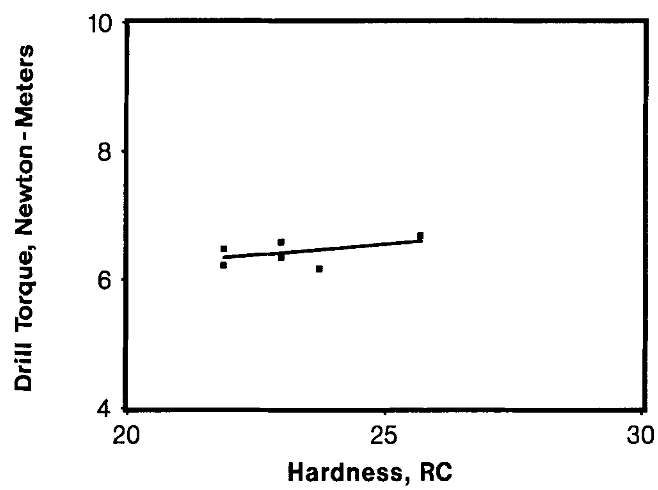


**Fig. 13** Effect of hardness on drill torque

In fact, under certain machining conditions, machinability actually improves with lower reduction ratios. To understand the mechanism of the effect of varying reduction ratios on machinability, examine Table 2, which indicates a general increase in hardness with higher reduction ratio. The effects of these changes in hardness on machinability are shown in Fig. 10-13. For the plunge test, Fig. 10 shows that with increasing hardness, there is an increase in the thrust force and calculated resultant force, but no significant change in the cutting force. Figure 11 shows that the speed for 20 minute tool life, $V_{20}$, is reduced with increased hardness. Finally, Fig. 12 and 13 show that there is a significant increase in drill force with hardness, yet the drill torque is not affected. Thus, the observed effect of reduction ratio on machinability is through the effect of hardness on machinability.

One interesting aspect of these results is that in the plunge test, the thrust force shows an effect of reduction ratio (or hardness); yet the cutting force does not. In the drill test, the drill force shows an effect, but not the drill torque. First, these results are internally consistent. Drill torque is closer to the cutting force whereas the drill force is similar to the thrust force; thus, similar forces in different tests yielded similar results. More interestingly, the thrust force is more affected by hardness than is the cutting force. This is understandable because the tip of the drill, for example, during cutting actually deforms or cold forms the material more than true cutting. Thus hardness, which is resistance to deformation, affects this aspect of machining more significantly. A similar argument is made for the thrust force in the plunge test. The cutting aspect, as measured by cutting forces, chip thickness, etc., on the other hand, is affected by several other factors. A clear cut effect of reduction ratio and, thus, hardness is not noticeable. A similar observation was made in other work (Ref 22), where changing the drill tip characteristics changed the drill force results, but not the drill torque (cutting) results.

The above reasoning also explains why chip thickness measurements did not yield any significant results, again confirming the internal consistency of various measurements on various aspects of machining. However, the chip thickness results do not explain the turning test results where the tool life tests yield better machinability for the steel with the lowest reduction ratio whereas the chip thickness is higher for this steel. This inconsistency is difficult to explain, but points out the complexity of tool life studies and machinability in general.


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