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# COMPUTER ANALYSIS OF OPTIMUM MACHINING SPEEDS

**Phillip J. Hecksel**
Lenco Computer Services
Southfield, Michigan

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## ABSTRACT

AN IMPORTANT CONSIDERATION in both manufacturing and design is machining cutting speed for metal removal operations. This function must be optimized to provide efficiencies in tooling procedures, as well as equipment and staff.

In order to optimize cutting speed, the impact of speed on life of the cutting tool must be predicted. This paper proposes the use of a mathmetical model to predict that impact. The remainder of this paper outlines the development of the proposed model.

A model has been developed using multiple linear regression analysis. It was performed with RS/1 on a VAX 11/785 computer with an R-squared coefficient of .94 indicating a significant level of confidence. Data for this model was extracted from: (1) physical properties of 195 subject materials and (2) empirical machining data published by other reseachers in the field. Selected categories for these properties were:

- Brinell Hardness
- Density
- Percent Elongation
- Specific Heat
- Machinability
- Depth of Cut
- Feed Rate

ALMOST ONE HUNDRED YEARS AGO, F.W. Taylor developed an equation for tool life, $V/VR = (TR/T)^n$, from empirical data generated in the machine shop where he worked. Expanding on Taylor's concept, query was made by the author as to whether advanced statistical techniques could be applied to empirical data from various reference texts to generate a mathemetical model for optimum cutting velocity thus creating the impetus for this project. While literature indicates that a considerable amount of work had been done in the area of tool life, little had been done with a large data base. Introduction of the computational tools available today and the use of a larger data base became the foundation for this project. While other researchers have accomplished a considerable amount of work in this field, only recently have the tools become available to generate the type of model used in this project.

In performing a machining operation on a turning machine, it is necessary to develop a theoretical equation relating materials and operating parameters. The reasons for this are: (1) there has been a significant decline in the number of skilled machinists available to determine the proper operating parameters and (2) due to world wide competition, it has become increasingly important to maximize productivity. There are three basic parameters required for machining operations: speed, feed, and type of cut. Speed is the velocity of the tool with respect to the work surface. It is usually measured in surface feet per minute (SFM). Feed is the radial rate of movement of the tool towards the rotational axis of the workpiece and is recorded in inches per revolution (IPR).

Type of cut is either roughing, semi-finishing, or finishing and is quantified by the depth of cut (DOC). A roughing cut is deeper than a finish cut. This project defines a roughing cut as 3.18 mm (.125 inches) where a finish cut is defined as .254 mm (.010 inches). Usually a machinist decides the type of cut and feed rate to use.

In order to achieve an accurate prediction, the dependency relationship between cutting speed, feed, type of cut, and material being machined must be established. The statistical tool used to find this relationship was multiple regression analysis. Simplistically, multiple regression analysis involves the determination of the best coefficients for a group of independent variables which will yield a given dependent variable. Multiple regression equations have the general form:

$$Y = a + b1X1 + b2X2 + \dots + bnXn$$

In this project, the speed (SFM) is the dependent variable (Y) and physical properties as well as the feed (IPR) and type of cut (DOC) are the independent variables (X1, X2, ... Xn).

To complete this project, two major tasks had to be accomplished. First, the independent variables (material properties) had to be established and the data for the metals collected. Second, access to a computer that had both sufficient capacity and speed, and an advanced statistical analysis program had to be secured. A DEC VAX-11/785 with the RS/1 statistical analysis - data base - plotting program obtained from Bolt Beranek and Newman met all the above specifications and was available at Lawrence Institute of Technology located in Southfield, Michigan. A major factor in the success of this project was the usage ease of this program. The ability to change a column of numbers with a limited number of key strokes and viewing the results instantaneously in the data base and graphs allowed more time for data research.

Originally nine independent variables were choosen because of their expected contribution or degredation to SFM. The variables considered were: Brinell Hardness Number (BHN), Percent Elongation (%EL), Density (DEN), Specific Heat (SPHT), Machinability (MACH), Type of Cut defined as Depth of Cut (DOC) and Feed Rate (IPR), and Electrical Conductivity. Each element was considered due to its known impact on SFM. Unfortunately there was a lack of electrical conductivity information on enough materials to warrant its inclusion into the data base. As the number of these variables increase, the determination of the regression coefficients becomes more difficult. To overcome this problem,a comprehensive statistical package was obtained from Bolt, Beranek, and Newman called RS/1. In addition to having the capabilities of graphic demonstration and data base manager characteristics, the package permits the multiple regression analysis needed to successfully complete this project.

Hardness is best defined as the resistance to forceable penetration or plastic deformation. A high brinell hardness value indicates a higher resistance to forceable penetration. More energy or a slower SFM is needed to cut the material.

Percent elongation is a measure of a metal's ability to return to its original shape after an applied force has been removed. Generally high elongations are found in ductile materials and are usually the cause of built-up-edge (BUE) which shortens tool life due to the BUE breaking off. Occurance of BUE usually requires a lower SFM to prevent it. In contrast, low elongation materials tend to cause excessive tool wear due to erosion.

Density is a measure of a material's mass per unit volume. Therefore at greater densities, a greater amount of mass exists which requires an increased amount of energy to remove. It becomes necessary to reduce SFM for higher density materials.

Specific heat refers to the amount of energy required to raise one unit mass of material one unit temperature. Frictional forces that occur during the machining process increase the temperature in the interface zone. Higher termperatures also increase the rate of solid state diffusion within the tool material which will decrease tool life. With high specific heat values, increased temperature can be transferred to the chip and be removed before being conducted to the workpiece.

Machinability is an index which refers to the ease or difficulty which a metal can be machined. At equivalent conditions a material with greater machinability will be able to cut at higher speeds.

Type of cut (DOC and IPR) are predefined due to manufacturing constraints. Higher DOC and/or higher IPR will result in lower SFM due to the increased volume of material being removed.

## DATA ANALYSIS

Data analysis was accomplished by entering data into an element array 195 by 9. An example is shown in Table 1. Columns 1 through 7 are the independent variables previously discussed. Column 8 is the SFM taken from reference literature and is also referred to as the "OBSERVED SFM". Column 9 is the calculated SFM which is the result of the regression analysis. The method used is multiple variable linear regression analysis. This involves the process of altering the coefficients until the variables and their coefficients closely resemble the mean of the dependent variable. This is where the power of the computer became so apparent. It allowed for rapid analysis that would be nearly impossible to accomplish manually. The program also makes suggestions as to which independent variables are not providing contribution to the final equation. The following outlines the final equation relating the independent variables to the dependent SFM:

$$\begin{aligned}\text{SFM} = &- (0.55402) \times \text{Brinell Hardness}\\ &+ (1.352065) \times \text{Percent Elongation}\\ &- (1648.1948869) \times \text{Density}\\ &+ (298.976469) \times \text{Specific Heat}\\ &- (1381.231435) \times \text{Machinability}\\ &+ (13125.195618) \times \text{Depth of Cut}\\ &- (197111.111111) \times \text{Feed Rate}\\ &+ 1538.894344\end{aligned}$$

Regression analysis demonstrated an R-squared coefficient of 94 percent with a significant level of .0001. The significant level indicates the probability of the equation being correct is .9999. Figure 1 illustrates the results of the regression analysis. Values on the X axis are "observed values". These were obtained from various reference sources. Values on the Y axis are "calculated values" which were obtained by substituting the data from table 1 into the equation listed previously. Figure 1 also contains the line Y = X. Ideally all data points should lie on this line. Data points above the line indicate the calculated speed is higher than the observed speed. Similarly, data below the line indicate the equation is predicting too low a speed. As can be seen on this graph, the majority of the points are very close to the "ideal line". The bar graphs shown in figure 2 - figure 4 are an indication of how well the data fits the ideal line. Percent difference between observed and calculated values is computed by summing the values in each major material grouping and calculating the delta difference on the totals. For the roughing type of cut, all materials analyzed except aluminums had a difference of less then ten percent. Semi-finishing cuts showed two materials (malleable and nodular iron) with a greater then ten percent difference. Finishing cuts indicated the greatest amount of difference. Material inconsistency is more noticable at a lighter depth of cut and feed rate which may cause higher differences. The degree of accuracy obtained from this model is unique in that it employs a large number of variables.

By using similiar concepts to those presented in this paper, it is perceived that a model could be developed with even a greater degree of accuracy.

## SUMMARY

After careful evaluation, it was determined that the impact of machining cutting speed on tool life can be accurately predicted using the outline mathemetical model/equation employing regression analysis techniques on specified variables.

## RECOMMENDATIONS

It is recommended that work continue using these same techniques for future analysis. Suggested considerations to use are: (1) a constant informational source and (2) a statistical program that has multi-regression, multi-variable, and curvilinear analysis capabilities. The data presented in Figure 1 indicates slight curvilinear tendencies. Curvilinear analysis, specifically exponential and logarithmic may afford a better fit. It is also believed that electrical conductivity may play an important role in the dynamic process of machining metals. It is the author's opinion that there may be an atomic interaction between the molecules that electrical conductivity values may display. By including these values in a sufficient data base and using a data analysis program, regression analysis should indicate if this is a valid hypothesis.

## ACKNOWLEDGEMENTS

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S.K. Bradley; Who was responsible for incisive surgery on the text.

| MATERIAL | BHN | PERCENT ELONGATION | DENSITY ($lb/in^3$) | SPECIFIC HEAT | MACHIN-ABILITY | ROUGHING | | SEMI-FINISH | | FINISHING | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | OBSER | PREDIC (SFM) | OBSER | PREDIC (SFM) | OBSER | PREDIC (SFM) |
| Plain Carbon Steels | | | | | | | | | | | |
| 1010 | 105 | 20 | .283 | .105 | .55 | 600 | 503 | 725 | 636 | 1025 | 965 |
| 1018 | 126 | 15 | .283 | .110 | .70 | 725 | 681 | 875 | 813 | 1250 | 1142 |
| 1045 | 175 | 12 | .283 | .113 | .65 | 575 | 568 | 700 | 710 | 975 | 1030 |
| 1060 | 180 | 10 | .283 | .105 | .60 | 550 | 510 | 650 | 642 | 925 | 971 |
| 1095 | 197 | 10 | .283 | .105 | .45 | 375 | 275 | 450 | 407 | 625 | 737 |
| Free Cutting Carbon Steels | | | | | | | | | | | |
| 1112 | 167 | 10 | .284 | .115 | 1.00 | 925 | 1052 | 1100 | 1185 | 1600 | 1514 |
| 1120 | 137 | 15 | .283 | .115 | .80 | 775 | 799 | 925 | 931 | 1300 | 1260 |
| 1140 | 170 | 12 | .282 | .115 | .70 | 625 | 640 | 750 | 772 | 1050 | 1102 |
| Alloy Steels | | | | | | | | | | | |
| 3140 | 195 | 24 | .283 | .110 | .55 | 425 | 375 | 500 | 507 | 725 | 836 |
| 4140 | 220 | 25 | .284 | .114 | .62 | 475 | 477 | 575 | 609 | 800 | 938 |
| 4620 | 179 | 23 | .282 | .110 | .59 | 500 | 473 | 600 | 605 | 850 | 935 |
| 8622 | 185 | 18 | .283 | .110 | .60 | 475 | 441 | 575 | 574 | 800 | 903 |
| 94B30 | 183 | 25 | .283 | .110 | .60 | 475 | 452 | 575 | 584 | 800 | 914 |
| Gray Cast Irons | | | | | | | | | | | |
| Class 20 | 156 | 0 | .260 | .100 | .90 | 850 | 948 | 1000 | 1080 | 1450 | 1409 |
| Class 45 | 262 | 0 | .260 | .100 | .52 | 400 | 364 | 475 | 496 | 675 | 826 |
| Class 60 | 302 | 1 | .260 | .100 | .45 | 325 | 245 | 400 | 378 | 550 | 707 |
| Malleable Irons | | | | | | | | | | | |
| 48005 | 203 | 5 | .260 | .122 | .80 | 650 | 747 | 775 | 879 | 1100 | 1209 |
| 60003 | 235 | 3 | .264 | .122 | .60 | 450 | 442 | 550 | 576 | 775 | 905 |
| Nodular Irons | | | | | | | | | | | |
| 60-45-15 | 183 | 15 | .250 | .110 | .60 | 500 | 508 | 600 | 641 | 850 | 963 |
| 100-70-03 | 270 | 3 | .252 | .110 | .60 | 375 | 399 | 450 | 531 | 625 | 861 |
| Aluminums | | | | | | | | | | | |
| 108 | 55 | 3 | .101 | .230 | 1.40 | 1900 | 2110 | 2300 | 2243 | 3250 | 2572 |
| A214 | 60 | 7 | .097 | .230 | 2.00 | 2650 | 2948 | 3200 | 3081 | 4500 | 3410 |
| 5052 | 68 | 14 | .097 | .230 | 1.90 | 2500 | 2841 | 3000 | 2974 | 4250 | 3303 |

TABLE 1

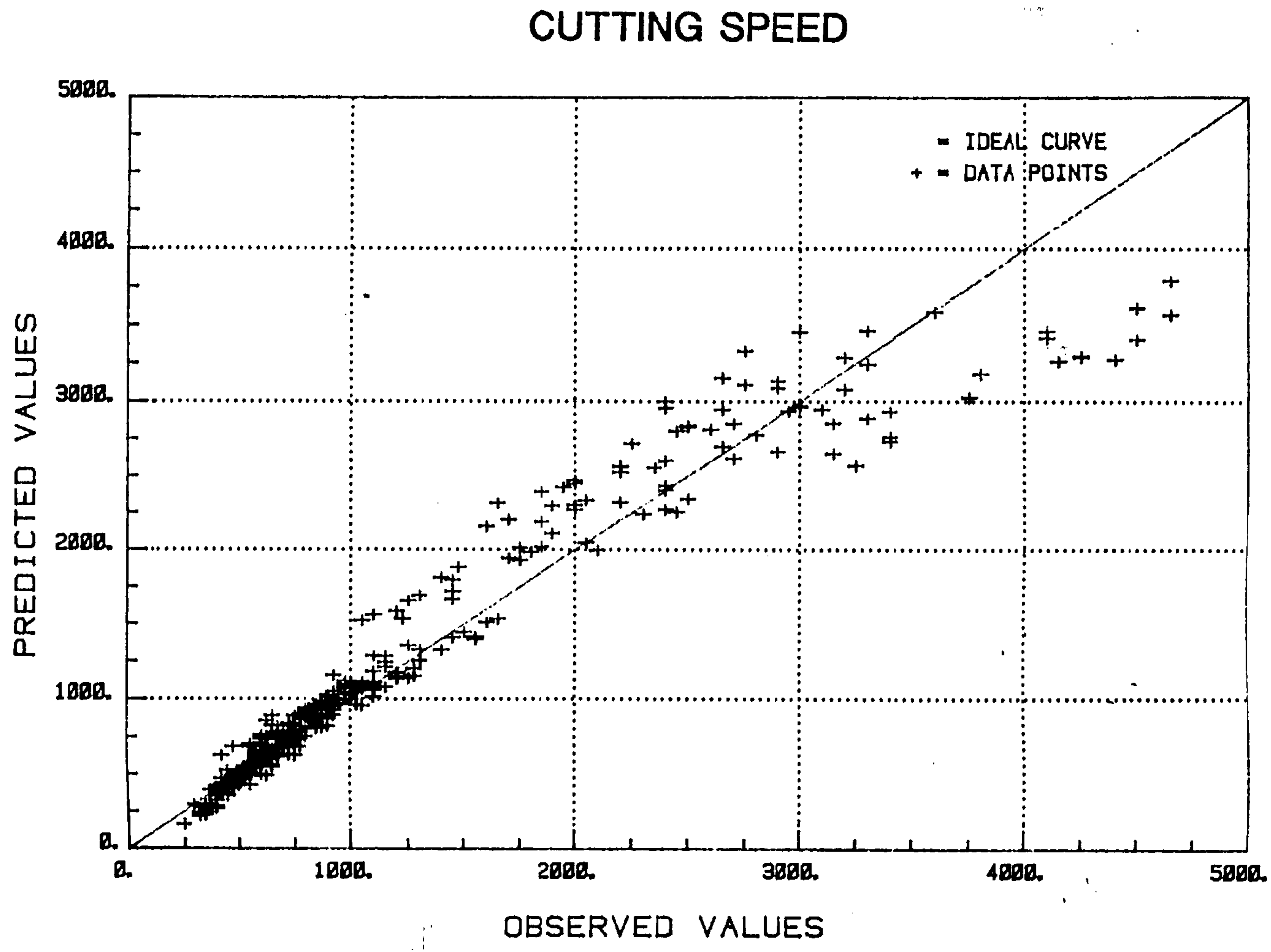
CUTTING SPEED
– = IDEAL CURVE
+ = DATA POINTS
PREDICTED VALUES
0.
1000.
2000.
3000.
4000.
5000.
OBSERVED VALUES
0.
1000.
2000.
3000.
4000.
5000.

FIGURE 1

## AVERAGE DIFFERENCE BETWEEN OBSERVED AND PREDICTED SFM — ROUGHING

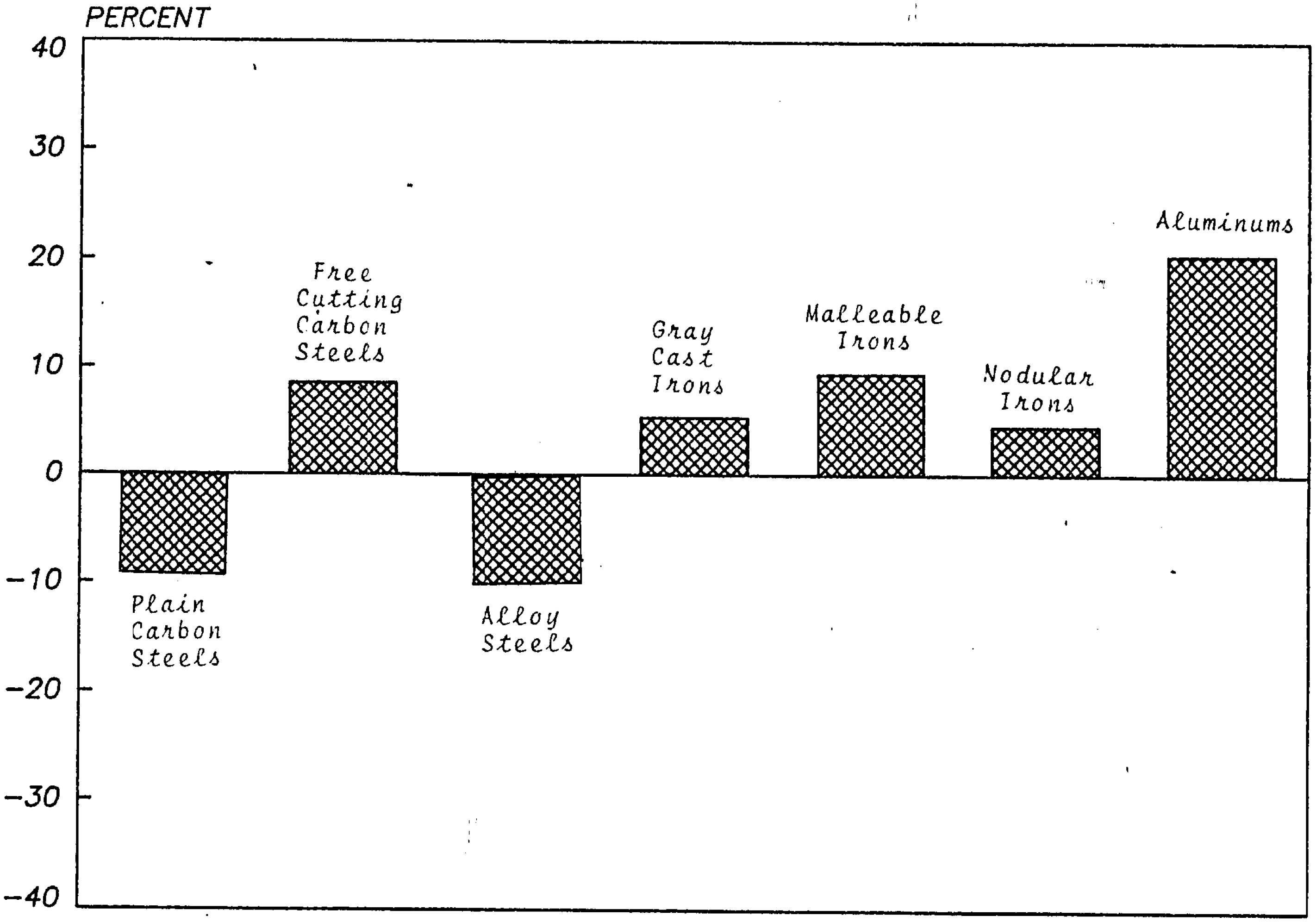

FIGURE 2

AVERAGE DIFFERENCE BETWEEN OBSERVED AND PREDICTED SFM – SEMI-FINISHING

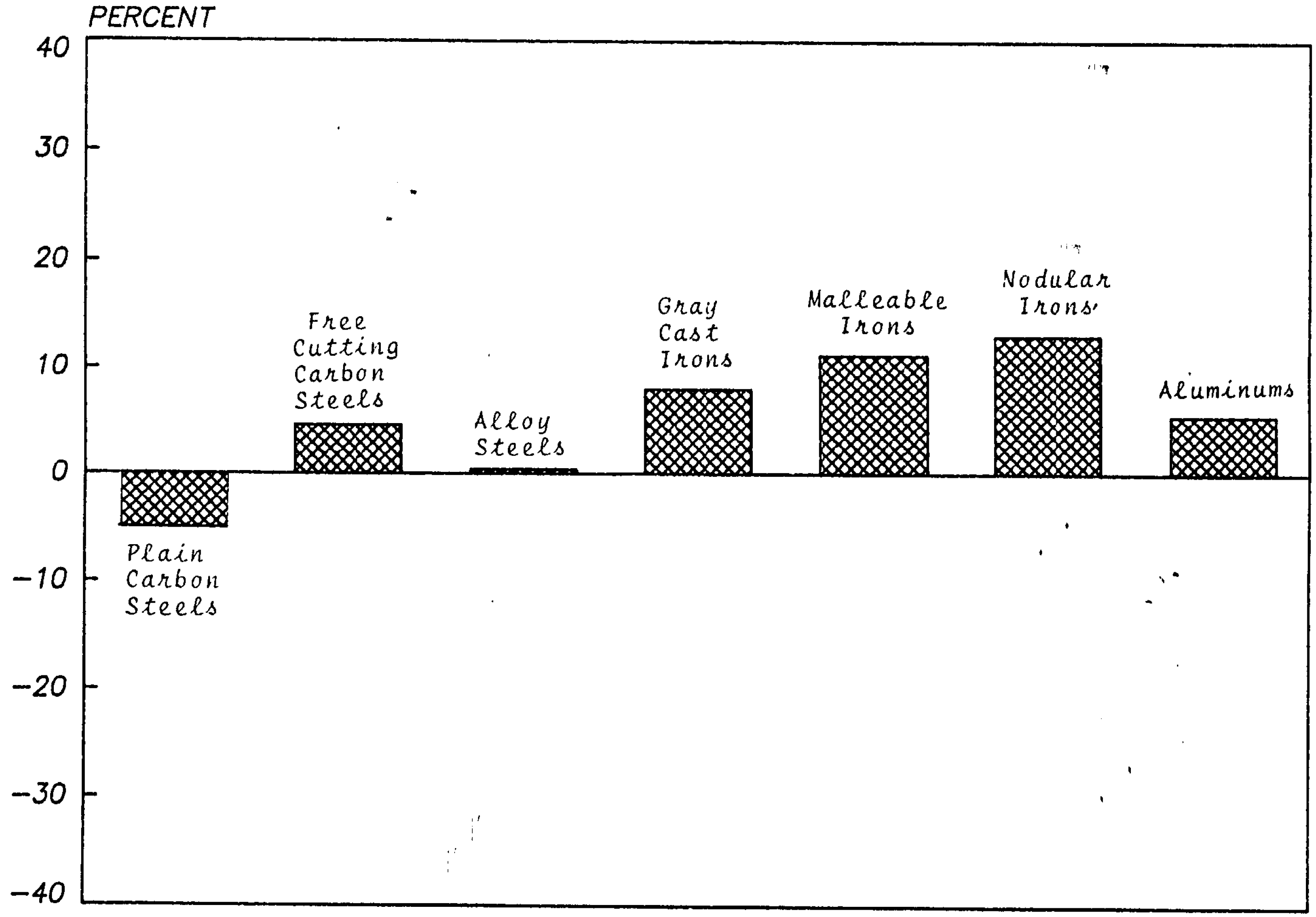

FIGURE 3

# AVERAGE DIFFERENCE BETWEEN OBSERVED AND PREDICTED SFM — FINISHING

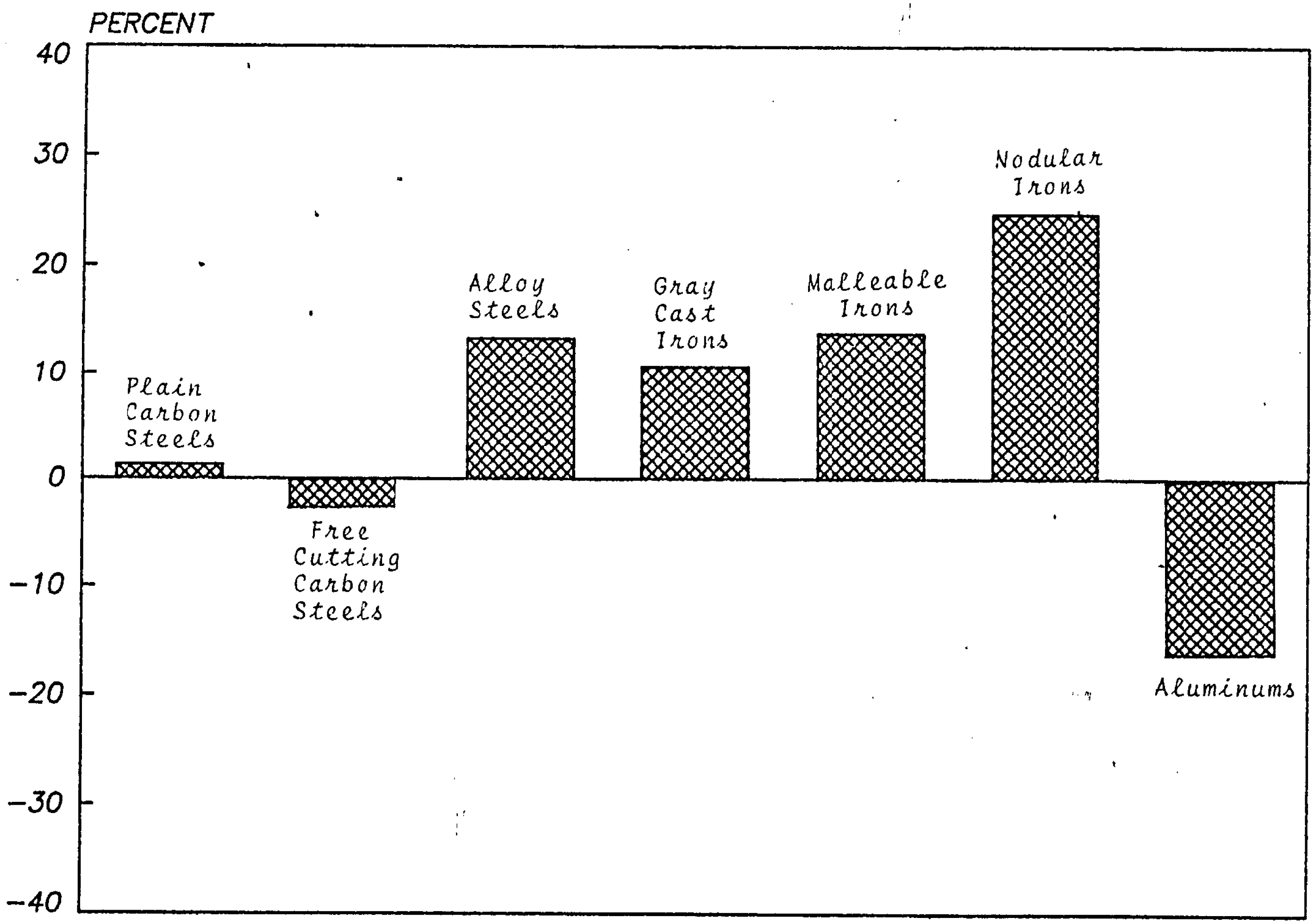

FIGURE 4

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