

Effect of Alloying Elements on Response of Nonoriented Electrical Steels to Stamping Operations

H. Yashiki and T. Kaneko

A suitable alloying design for improving the punchability of nonoriented electrical steels containing 0.1% Si was investigated. The appropriate addition of sulfur to steels containing relatively high manganese content is very useful in obtaining good punchability without detrimental effects on magnetic properties.

1 Introduction

NONORIENTED electrical steels are widely used as core laminations for motors and transformers. During punching operations, the precision of the core size becomes poor and the burr height on the punched edge tends to increase as the punching die wears.[1] These deviations during punching occasionally result in difficult core assembly and deterioration of magnetic properties. Punching die tools should be repaired when the burr height exceeds some preestablished criteria. Therefore, improvement of the punchability of electrical steels, thus preventing die wear and burr formation, is important to the efficiency of punching operations. This goal is particularly important in low-silicon nonoriented electrical steels with good punchability, because they are used in large quantities due to their high magnetic induction and economy.

It is well known that insulation coatings containing some kind of organics are effective in improving punchability.[2,3] The strength level of steels is also affected,[1] although this effect is less than that of surface coatings.[3] In spite of these situations, control of mechanical properties is important, because the composition of the steels itself could enhance the coating effect of punchability, and there are numerous nonoriented electrical steels without coatings.

An increase in strength and carbide precipitation are effective for improving punchability.[4,5] However, these methods are generally undesirable for magnetic properties, especially in the case of fully processed grades that do not undergo a stress-relief annealing.

In the present study, the influences of carbon, phosphorus, and sulfur on punchability are investigated. This study is directed toward the development of low-silicon nonoriented electrical steels with improved punchability compatible with good magnetic properties.

H. Yashiki and **T. Kaneko,** Sheet Materials Research Laboratory, Iron & Steel Research Laboratories, Sumitomo Metal Industries, Ltd., Amagasaki, Japan.

2 Experimental Procedure

2.1 *Materials*

Table 1 shows the chemical composition of test steels that were prepared by vacuum melting. The steels can be grouped into three categories. Group I (Steels 1 through 4) is comprised of ultra-low carbon and low-sulfur steels; Group II (Steels 5 through 9) is comprised of ultra-low carbon and high-sulfur steels, and Group III (Steels 10 and 11) is made up of comparatively high carbon and low-sulfur steels. Phosphorus contents vary from 0.008 to 0.175% in each group. The steels in Group II

Table 1 Chemical Composition of Test Steels

	Composition, wt.%						
Steel	C	Si	Mn	P	S	sol.Al	N
Group I							
1	0.0019	0.15	0.25	0.021	0.007	0.001	0.0033
2	0.0022	0.15	0.25	0.078	0.007	0.001	0.0032
3	0.0027	0.15	0.26	0.170	0.006	0.001	0.0030
4	0.0017	0.15	0.25	0.078	0.016	0.001	0.0029
Group II							
5	0.0020	0.07	0.35	0.008	0.027	0.001	0.0026
6	0.0018	0.06	0.30	0.077	0.026	0.001	0.0038
7	0.0022	0.14	0.41	0.080	0.032	0.001	0.0032
8	0.0026	0.15	0.35	0.175	0.030	0.001	0.0032
9	0.0018	0.14	0.40	0.170	0.030	0.001	0.0038
Group III							
10	0.037	0.12	0.26	0.007	0.001	0.001	0.0051
11	0.046	0.12	0.26	0.128	0.003	0.001	0.0042

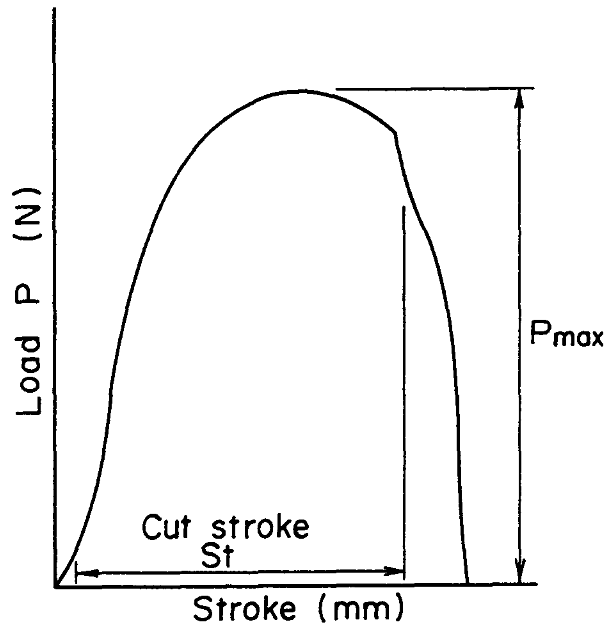

Fig. 1 Load-stroke curve of single punching test.

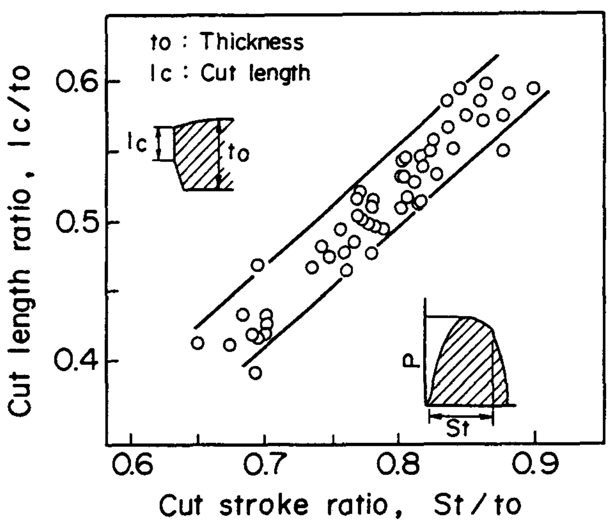

Fig. 2 Relationship between cut length ratio, *lc/to*, and cut stroke ratio, S_t/to.

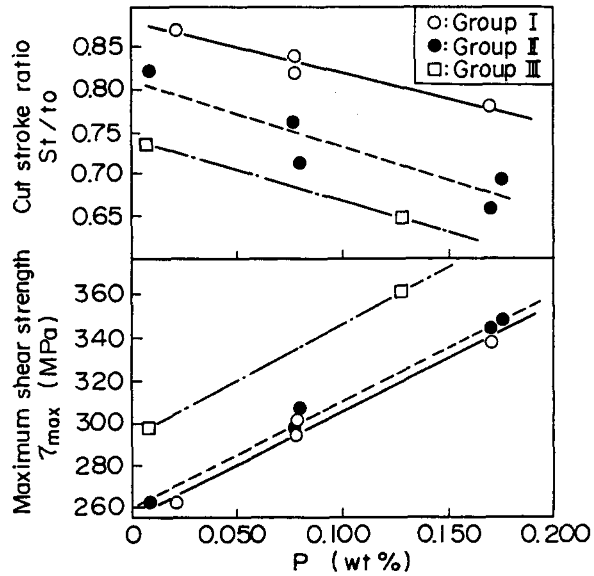

Fig. 3 Effect of alloying elements on cut stroke ratio, S_t/to, and maximum shear strength, τ_{max}.

contain relatively high manganese contents for the purpose of coarsening MnS precipitates.

The ingots were hot forged to 15 mm in thickness after heating at 1250 °C for 30 min. The slabs were reheated to 1250 °C and kept for 30 min, then hot rolled to 4 mm in thickness by three passes with the finishing temperature of 800 °C. To simulate the coiling condition, the hot bands were air cooled to 650 °C after hot rolling, annealed for 30 min in a furnace kept at 650 °C, and cooled to room temperature at a rate of 20 °C/hr. The hot bands were machined from both surfaces to 2.3 mm in thickness and cold rolled to 0.5 mm in thickness with a total reduction of 78%. The cold rolled sheets were finally annealed in a salt bath at 700 °C for 1 min.

2.2 *Evaluation of Punchability*

Punchability was evaluated mainly by a single punching test for the sake of simplicity and specimen saving. Test conditions were as follows:

- Die material: Alloy tool steel (SKD-11)
- Blank size: 14 mm in diameter
- Punching speed: 60 strokes/min
- Die clearance: 14%
- Punching oil: Kerosene

The cut stroke ratio, S_t/to and maximum shear strength, τ_{max}, which were derived from a load-stroke curve as shown in Fig. 1, were used as the parameters of punchability. S_t is defined as a stroke between the abrupt rising and falling points of a load, and *to* is the thickness of the specimen. As shown in Fig. 2, the cut stroke ratio S_t/to has a good correlation with the cut length ratio, *lc/to* (*lc* is a length of cut portion in thickness at the punched edge). An increase in cut length ratio results in increased die wear,[1] so the higher cut stroke ratio S_t/to is undesirable for punchability. The maximum shear strength τ_{max} is obtained from the maximum load P_{max} derived by the area of cross section at the punched edge. An increase in τ_{max} also promotes die wear.

To clarify the relation between burr formation and S_t/to or τ_{max}, a continuous punching test was undertaken using strip specimens with different combinations of S_t/to and τ_{max}. The conditions of the continuous punching test were as follows:

- Die material: Alloy tool steel (SKD-11)
- Blank size: 20 mm in diameter
- Punching speed: 60 strokes/min
- Die clearance: 7%
- Punching oil: Kerosene

Table 2 Cut Stroke Ratio and Maximum Shear Strength of Specimens Used for Continuous Punching Tests

Specimen	Cut stroke ratio, S_t/to	Maximum shear strength (τ_{max}), MPa
A	0.93	291
B	0.85	314
C	0.76	298

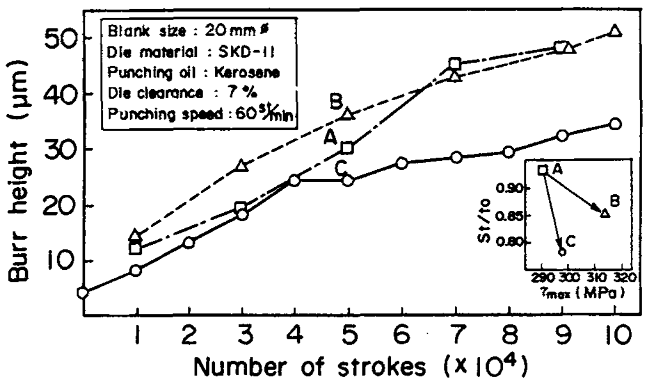

Fig. 4 Changes in burr height during continuous punching test.

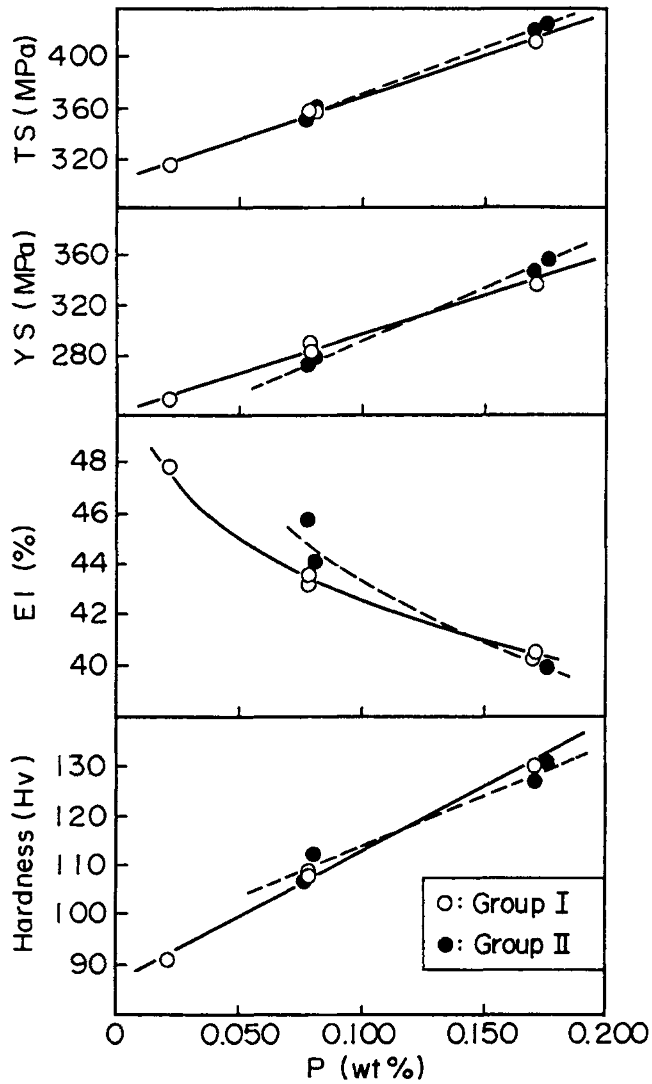

Fig. 5 Effect of sulfur and phosphorus on mechanical properties.

2.3 *Measurement of Magnetic Properties and Mechanical Properties*

The magnetic properties were measured in 0° and 90° directions from the rolling direction using a miniature Epstein specimen of 10 mm in width and 100 mm in length that was punched from the annealed sheet. The mean values of 0° and 90° directions were finally used as a parameter. Mechanical properties and microstructures were also examined after final annealing. Tensile tests were carried out in the rolling direction, and Vickers hardness was measured on the rolling surface (load: 9.8 N). The ferrite grain size and amounts of inclusions were examined by JIS methods[6,7] on a cross section parallel to the rolling direction.

3 Experimental Results

3.1 *Single Punching Test*

Figure 3 shows the effect of alloying elements on cut stroke ratio S_t/to and maximum shear strength τ_{max} in the single punching test. At first, it is clear that phosphorus addition results in a decrease in S_t/to and an increase in τ_{max}, irrespective of the material group. At the same phosphorus level, Group III specimens (steels with relatively high carbon contents) exhibit the lowest value of S_t/to, but it brings about higher τ_{max}. On the other hand, sulfur addition (Group II) is effective in decreasing S_t/to, with no effect on τ_{max}.

Generally, both the increases in S_t/to and τ_{max} are unfavorable for punchability. In this respect, it is difficult to judge the effects of phosphorus and carbon on a punching performance because these alloying elements induce opposite tendencies for the two parameters. The effect of sulfur addition, which lowers S_t/to without any increase in τ_{max}, seems to be useful for improving punchability.

3.2 *Continuous Punching Test*

The continuous punching test was performed to examine which of the two parameters, S_t/to and τ_{max}, is dominant in burr formation. Three kinds of strip specimens of 0.5 mm in thickness with different combinations of S_t/to and τ_{max} were prepared, as shown in Table 2. Figure 4 shows the changes in burr height during the continuous punching test. The slowest progress of burr height is obtained in Specimen C, which has the lowest S_t/to and almost same τ_{max} as that in Specimen A. Although the S_t/to ratio of Specimen B is relatively small, this favorable effect might be compensated by its higher τ_{max} value, and consequently, similar burr formation as that of Specimen A would be likely to occur. It could be concluded that the reduction of S_t/to without an increase in τ_{max} is the best method of improving the actual punching process. As mentioned previously, this combination can be achieved by sulfur addition.

3.3 *Mechanical Properties and Microstructure*

The effects of alloying elements on mechanical properties, ferrite grain size, and amounts of inclusions are shown in Fig. 5, 6, and 7, respectively. As shown in Fig. 5, mechanical properties significantly depend on phosphorus content. An increase in phosphorus content results in an increase in tensile strength, yield strength (upper yield point), and hardness and conversely a decrease in elongation. These behaviors are generally explained by the solution hardening effect of phosphorus.[8] Grain refinement due to the addition of phosphorus as shown in Fig. 6, should also take into account to some extent, although the effect of grain refining in this study, estimated from the Petch's equation derived by Morrison,[9] is not significant compared to the effect of solution hardening.

In this study, the influences of sulfur additions on mechanical properties and ferrite grain size are negligibly small. Sulfur additions usually lead to a fine grain structure due to an increase in fine MnS precipitates. Relatively high manganese contents in steels with high sulfur contents (Group II) would prevent the precipitation of fine MnS.[10] No significant solution hardening due to manganese is detected within the variation of manganese contents in this study.

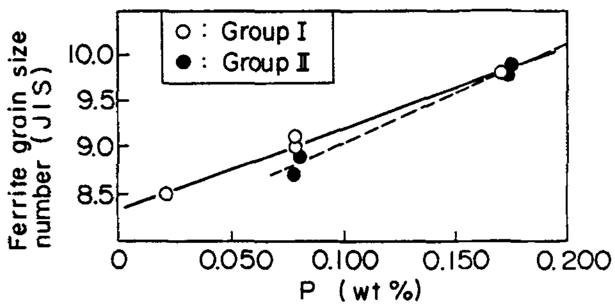

Fig. 6 Effect of sulfur and phosphorus on ferrite grain size.

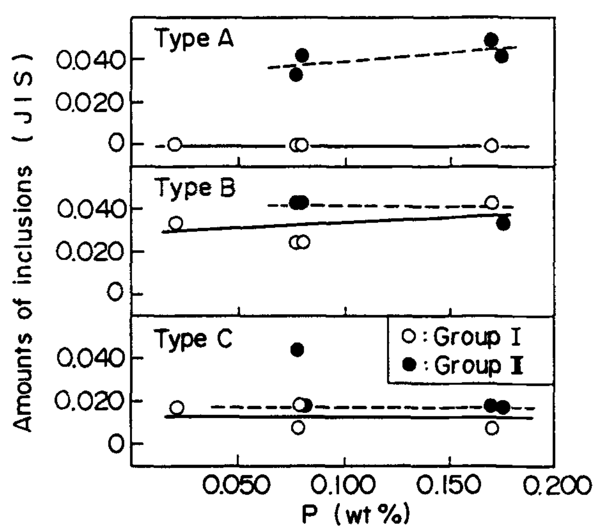

Fig. 7 Effect of sulfur and phosphorus on the amounts of inclusions.

Figure 7 shows the influence of sulfur and phosphorus on the amounts of inclusions. Inclusions are of three types according to JIS classification.[7] The amounts of Type A inclusions, mainly consisting of elongated MnS, are strongly affected by sulfur content and are independent of phosphorus content. Sulfur and phosphorus contents have no effect on the amounts of Types B and C inclusions, which are identified as granular oxides such as MnO.

3.4 *Magnetic Properties*

Figure 8 shows the influences of sulfur and phosphorus contents on magnetic properties in ultra-low carbon steels. Core loss, $W_{15/50}$, tends to increase slightly with sulfur and phosphorus additions. The deterioration of core loss via phosphorus addition would be caused by the grain refinement due to the solid solution of phosphorus, and an increase in MnS particles with a sulfur addition would prevent a domain wall migration. These alloying elements do not affect magnetic induction, B_{50}. The deterioration of core loss due to sulfur and phosphorus additions are so small that they can be regained by a slight increase in annealing temperature.

4 Discussion

On the basis of single punching test results, the effects of carbon, phosphorus, and sulfur on the two parameters for punchability assessment, S_t/to and τ_{max}, can be exhibited schematically as in Fig. 9. Phosphorus additions result in a decrease in S_t/to, but in an increase in τ_{max} at the same time. Sulfur additions are effective in reducing S_t/to without a change in τ_{max}. Carbon addition provides a similar effect as a phosphorus addition, although its effect is halfway between phosphorus and sulfur. The result of continuous punching tests reveal that a decrease in S_t/to

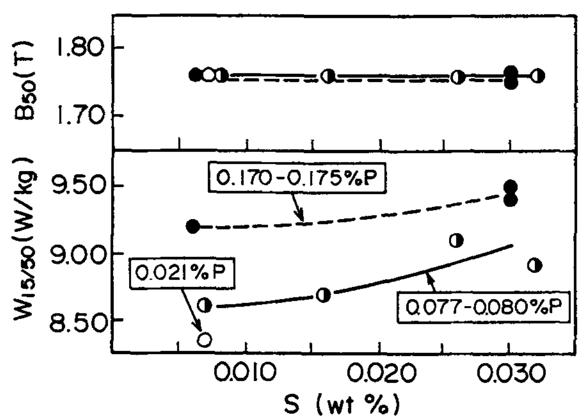

Fig. 8 Effect of sulfur and phosphorus on magnetic properties.

without an increase in τ_{max} is effective in preventing burr formation. From the viewpoint of the actual punching operation, sulfur additions are considered more useful than phosphorus or carbon additions. The harmful effect of sulfur additions on magnetic properties can be easily avoided, if appropriate countermeasures, such as manganese additions, are adopted.

The effects of alloying elements on S_t/to and τ_{max} can be interpreted from the behaviors of mechanical properties and microstructures. S_t/to and τ_{max} could be correlated with the tensile strength and elongation obtained by tensile test.[11] Figure 10 shows good correlation between τ_{max} and tensile strength. An increase in τ_{max} by a phosphorus addition can be explained by the increase in tensile strength. On the other hand, a sulfur addition has no effect on tensile strength. Therefore, τ_{max} in high-sulfur steels remains the same as in low-sulfur steels. Figure 11 shows the relationship between S_t/to and elongation. A decrease in S_t/to by phosphorus addition would be caused mainly by a decrease in elongation. However, S_t/to is affected not only by elongation, but also by sulfur content, and the difference in S_t/to due to the sulfur level cannot be explained by the changes in mechanical properties.

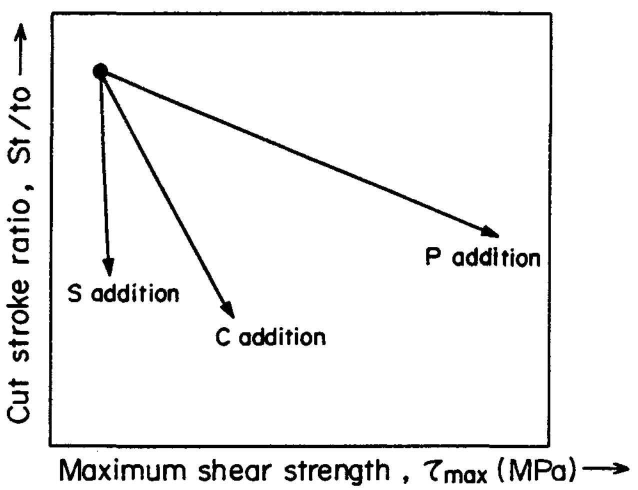

Fig. 9 Effect of alloying elements on cut stroke ratio, S_t/to, and maximum shear strength, τ_{max}.

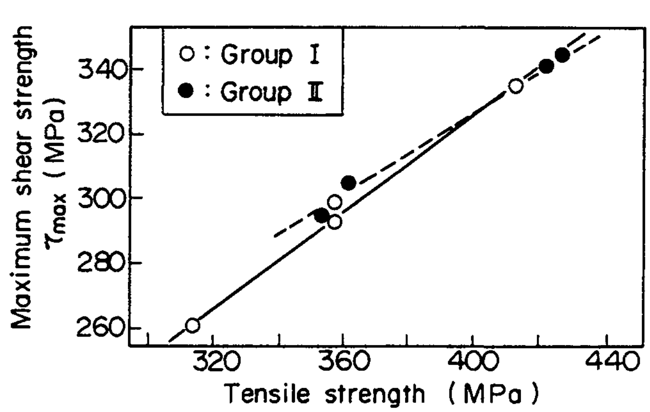

Fig. 10 Relationship between maximum shear strength, τ_{max}, and tensile strength.

Figure 12 shows the influence of the amounts of Type A inclusions on S_t/to. Comparing in the same phosphorus level where almost the same elongation is obtained, S_t/to tends to decrease with an increase in Type A inclusions. The effect of sulfur on S_t/to could be understood from this aspect. It is reported that Type A inclusions such as elongated MnS reduce ductility, particularly in the transverse and thickness directions.[12]

There are no data available on the mechanical properties and microstructures in high-carbon steels (Group III), but the effects of carbon additions on S_t/to and τ_{max} can be considered as follows. Generally, carbon additions lead to higher tensile strength and lower elongation in steels. These behaviors are essentially the same as obtained with phosphorus additions and result in an increase in τ_{max} and a decrease in S_t/to. In addition, an increase in cementite in higher carbon steels would reduce S_t/to in the same manner as MnS. This is why carbon additions yield the mixed features of phosphorus and carbon additions.

In spite of a lot of studies on the evaluation of actual punchability by single punching tests,[11,13,14] a commonly acceptable method has not been established. Sukegawa[13] and Mizuno *et*

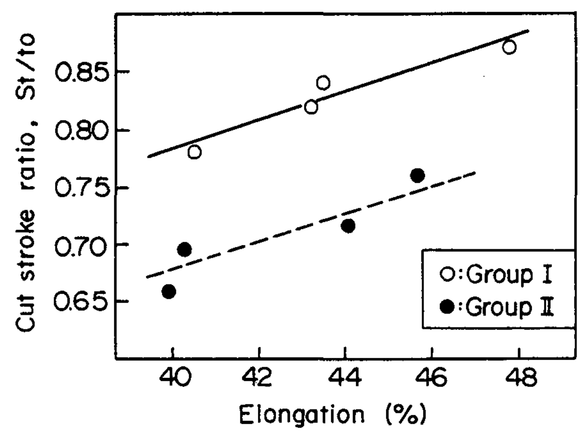

Fig. 11 Relationship between cut stroke ratio, S_t/to, and elongation.

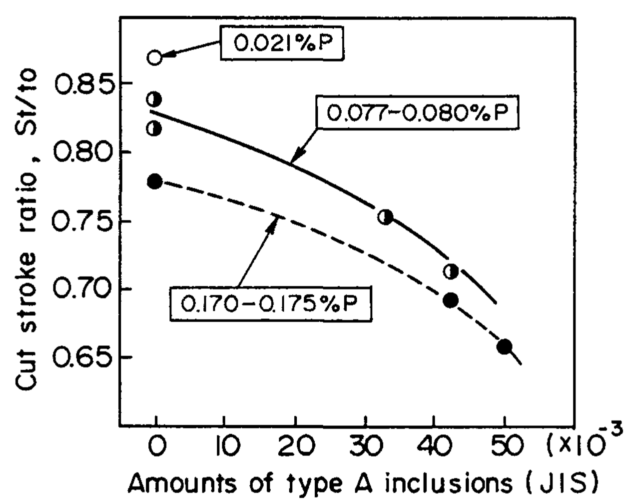

Fig. 12 Effect of the amounts of Type A inclusions on cut stroke ratio, S_t/to.

al.[14] reported that continuous punchability is improved with a decrease in the shearing energy, which is defined as the area of load-stroke curve in a single punching test. Because a decrease in S_t/to without an increase in τ_{max} corresponds to a reduction in shearing energy, the results of the present study agree with those of Sukegawa and Mizuno *et al.* Conversely, Nakamura *et al.* reported that the actual punchability cannot be evaluated by shearing energy.[3] It is open to future investigations to determine which parameters in single punching tests are valid assessments of actual punchability.

5 Conclusion

The effect of alloying elements on punchability of low-silicon nonoriented electrical steels have been investigated. The following conclusions were obtained. In single punching tests, phosphorus additions increase the maximum shear strength and decrease the cut stroke ratio. This behavior can be interpreted by the increase in strength and the reduction in elongation.

Sulfur additions decrease the cut stroke ratio without an increase in maximum shear strength. A decrease in the cut stroke ratio by sulfur additions can be explained by a decrease in ductility in the thickness direction as a result of an increase in Type A inclusions such as MnS.

The effects of carbon additions are essentially similar as phosphorus additions, but the increase in maximum shear strength is rather small. As for the changes in cut stroke ratio, an increase in cementite might be taken into account. Burr formation during continuous punching tests is effectively suppressed by a decrease in cut stroke ratio without an increase in maximum shear strength in the materials. On the basis of these results, sulfur additions to steels containing relatively high manganese contents are considered to be very useful for improving the actual punchability without harming magnetic properties.

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