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ROLE OF NIOBIUM IN ADVANCED SHEET STEELS FOR AUTOMOTIVE APPLICATIONS

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Abstract

Two major drivers for the use of newer steels in the automotive industry is fuel efficiency and increased safety performance. Fuel efficiency is mainly a function of weight of steel parts, which in turn, is controlled by gauge and design. Safety is determined by the energy absorbing capacity of the steel used to make the part. All of these factors are incentives for the U.S. automakers to use both Highly Formable and Advanced High Strength Steels (AHSS) to replace the conventional steels used to manufacture automotive parts in the past.

Highly Formable Steels are generally ultra-low carbon steels fully or partially stabilized by alloying elements such as Ti or Nb. The role of Nb in these steels will be described in this paper.

AHSS is a general term used to describe various families of steels. The most common AHSS is the dual-phase steel that consists of a ferrite-martensite microstructure. These steels are characterized by high strength, good ductility, low tensile to yield strength ratio and high bake - hardenability. Another class of AHSS is the multi-phase steel which have a complex microstructure consisting of various phase constituents and a high yield to tensile strength ratio. Transformation Induced Plasticity (TRIP) steels is the latest class of AHSS steels finding interest among the U.S. automakers. These steels consist of a ferrite-bainite microstructure with significant amount of retained austenite phase and show the highest combination of strength and elongation, so far, among the AHSS in use. The role of Nb in all of the above families of AHSS will be discussed in the paper.

Introduction

The use of advanced steels in the automotive industry has grown explosively over the last decade. Their applications can be broadly classified into: outer body panels and body-in-white parts. In the case of outer body panels, the major driver has been continuing the quest for fuel economy and hence, weight reduction. This translates to more formable steels for manufacture of complex design parts as well as part consolidation. In addition, reduction of gauge for weight savings has led to the use of high strength IF and IF-bake hardenable steels. For the body-in-white parts, major drivers have been reductions of weight as well as increased emphasis on safety performance. In these applications, the focus, therefore, has been on first, development of higher and higher strength steels with good formability for gauge reduction, and second, in steels with higher energy absorption capacity for safety enhancement parts. Steels for the first type of application include multi-phase (complex phase) steels and dual phase steels. The second type of applications include dual phase but particularly the Transformation Induced Plasticity (TRIP) steels.

In this paper, the role and use of Nb in each of these various types of advanced steels for automotive applications will be discussed.

IF Steels

The effect of Nb in IF steels can be broadly classified into three categories: strengthening effect, effect on isotropicity and effect on coatability.

Formable IF Steels

For formable IF steels, only the second two effects are important. One effect of Nb, which has been well established in the literature, is its effect on crystallographic texture [1-5]. Nb improves the r_{45} values and as a result, there is a decrease in Δr when compared to Ti-IF steels. Typical effect of Nb on both Δr and ΔEl is given in Figure 1 [6]. Δr is defined as:

$$\Delta r = (r_L + r_T - 2r_D) / 2 \qquad (1)$$

and is a measure of the isotropicity of r-value among the various rolling directions. Similarly ΔEl is defined as:

$$\Delta EL = (El_L + El_T - 2El_D) / 2 \qquad (2)$$

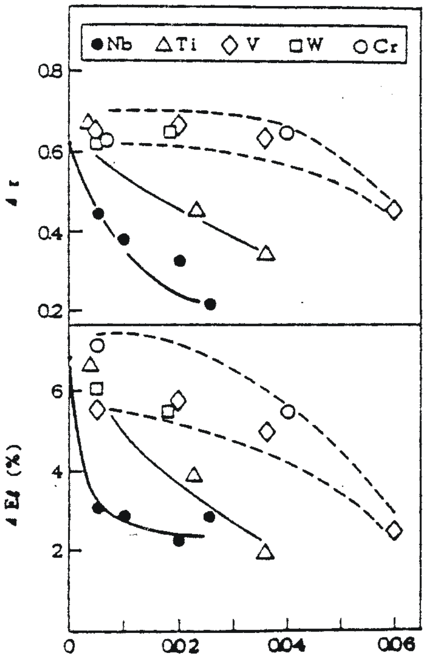

Figure 1. Effect of various alloying additions on Δr and ΔEl.

It is clear that Nb has the most significant effect on reducing Δr as well as ΔEl. In other words, steels containing Nb are more isotropic. For reasons not completely understood, steels with lower Δr perform better during forming. As a result, Nb containing IF steels lead to improved stampability and lower scrap loss.

The second effect of Nb in IF steels is that it affects the galvannealing reaction. There are many studies reported in the literature documenting the beneficial effect of Nb on the coatability and coating performance of galvannealed steels. Recent work by Chang [7] has shown the effect of Nb on the galvannealing reaction in Ti –IF vs Ti + Nb – IF steels.

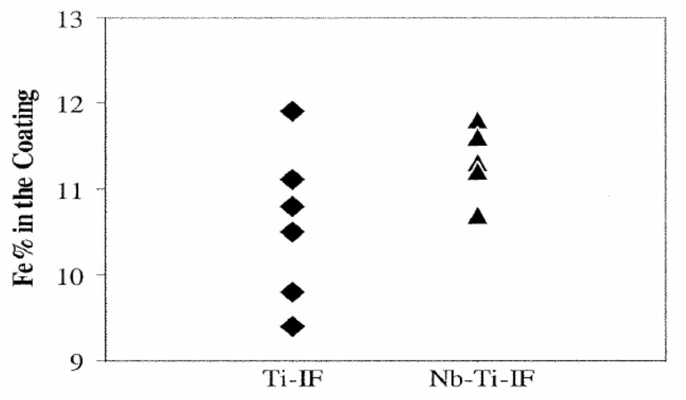

Figure 2. Effect of Nb on the galvannealing reaction in IF steels.

These results show that while under certain conditions, Ti –IF steels can galvanneal similarly to Ti + Nb – IF steels, the control of the galvannealing reaction and thus the coating structure is more difficult. This is clearly shown in the galvannealed coating microstructure in Figure 3 [7] Nb + Ti – IF steels show a more uniform coating microstructure with no “outburst” areas. The consequent effect on coating performance is shown in Figures 4 and 5. In Figure 4 the coating adherence of Nb – Ti IF steels is seen to be superior to Ti – IF steels from the classic work of Tokunaga et al. [8]. In Figure 5, the effect on powdering is shown from the work of Cheng [7].

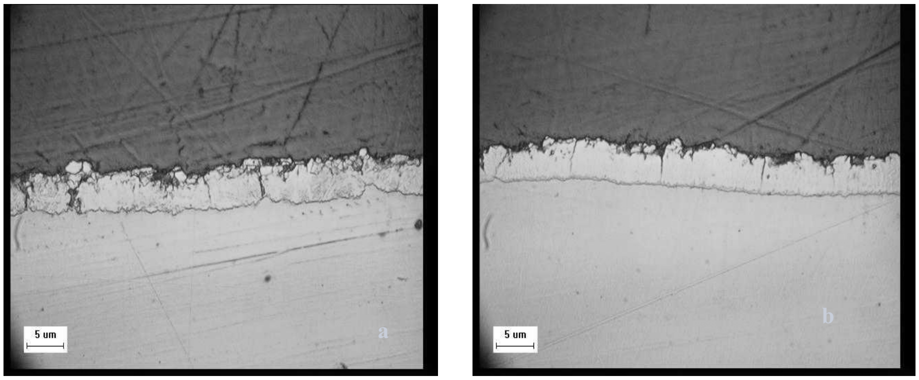

Figure 3. Effect of Nb on the galvanneal coating microstructure in IF steels.

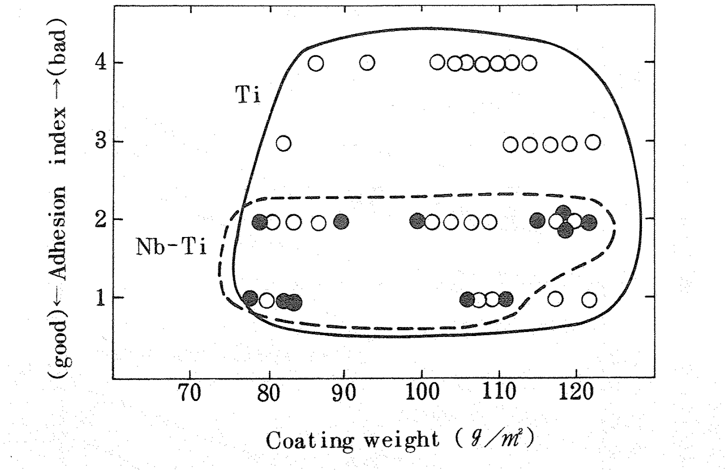

Figure 4. Coating adherence of Ti – IF and Nb + Ti – IF steels.

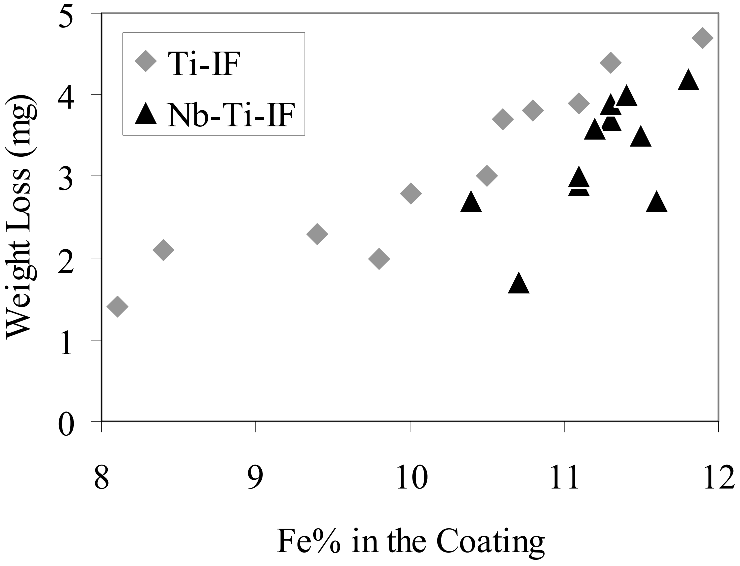

Figure 5. Effect of Nb on the powdering characteristics of IF steels.

The mechanism by which Nb reduces the "outburst" reaction is complicated, and involves several phenomena. "Outburst" occurs due to the extreme cleanliness of the grain boundaries in IF steels and the consequent enhanced diffusion through the grain boundaries. Hence, any factor, which reduces the cleanliness of grain boundaries, reduces "outburst" reaction. First in Ti – IF steels, Ti scavenges P by formation of Fe – Ti – P leaving no P on the grain boundaries while in Nb-containing IF steels, some P is left in the grain boundary, thus reducing the outburst reaction [9]. In addition, work at the Univ. of Pittsburgh by DeArdo et al. [10] has shown segregation of Nb to grain boundaries, again reducing the outburst reaction. Finally, recent work [11], using XPS and GDS techniques, has shown that Nb also segregates to the surface and affects the inhibition layer and thus the galvannealing reaction.

Composition and properties of a typical formable IF steel is shown in Table I.

Table I. Typical composition and properties of a formable IF steel.

Typical Composition (Wt. %)

	C	Mn	P	S	Si	**Nb**	Ti
340 +	.0025	.5	.035	.010	.03	**.025**	.015
440 +	.0030	1.6	.09	.015	.10	**.030**	.020

Typical Properties

	Tensile Strength (MPa)	Yield Strength (MPa)	Total Elongation (%)	R – bar	n - bar
340 +	365	195	37	1.6	.24
440 +	>440	285	35	1.3	.22

High Strength IF Steels

For high strength IF steels, in addition to its effects on isotropicity and galvannealing, Nb also contributes to strengthening through finer grain size and precipitation hardening. This is well documented in the literature [12] and a typical effect of Nb on yield strength is shown in Figure 6.

Composition and properties of typical high strength IF steels are shown in Table II.

Table II. Typical composition and properties of high strength IF steels.

Typical Composition (Wt. %)

C	Mn	P	S	Si	Al	N	Ti	**Nb**
0.004/0.005 max	0.10/0.25	0.02 max	0.015 max	0.02 max	0.02/0.07	0.005 max	0.01/0.025	**0.022/0.035**

Typical Properties

Tensile Strength (MPa)	Yield Strength (MPa)	Total Elongation (%)	R - bar	n - bar
290 – 310	140 – 160	45 – 50	1.6 – 1.8	0.24 - 0.26

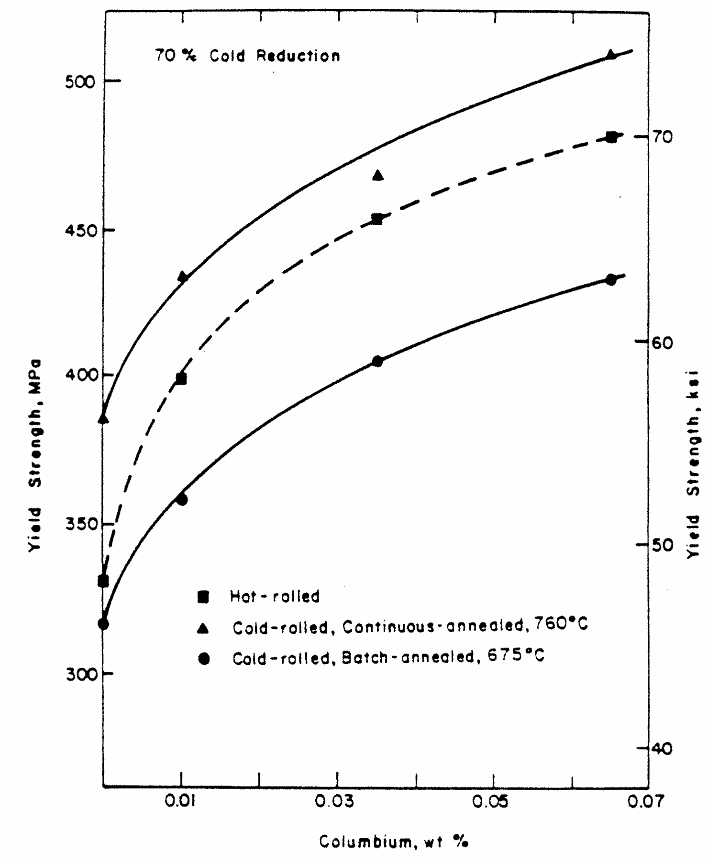

Figure 6. Effect of Nb on yield strength.

Bake Hardenable "IF" Steels

Almost all bake hardenable "IF" steels are produced through the Nb addition route for bake hardenability. This is because some C (5 – 20 ppm) is needed to be in solution [13, 14]. The two ways to have C in solution in a "IF" steel are:

1) to leave the C in solution during steelmaking by adding the right amounts of alloying elements to combine with N, S and C, or
2) 2) to combine all the interstitials initially and then redissolving some of the components during annealing to put some C in solution. Both of these methods are best achieved by using Nb to combine with C. In addition, Nb provides strengthening, improved isotropicity and better galvannealing as noted earlier.

Composition and properties of some bake hardenable "IF" steels are shown in Table III.

Table III. Typical composition and properties of a IF steel.

Typical Composition (Wt. %)

	C	Mn	P	S	Si	**Nb**	Ti
180 Y BH	0.0035	0.30	0.02	0.015	0.03	**0.005**	0.005
340 T BH	0.003	0.50	0.035	0.015	0.03	**0.005**	0.006

Typical Properties

	Tensile Strength (MPa)	Yield Strength (MPa)	Total Elongation (%)	R – bar	n - bar
180 Y	325	200	41	1.45	.2
340 T	355	230	40	1.40	.2

While Nb addition has several advantages in IF steels as outlined above, there are some issues with Nb addition as well. The first is the higher incidence of surface defects such as slivers in Nb containing IF steels than in Ti only IF steels. While the reasons are not completely clear, it is believed to be related to the interaction and behavior of the mold powder as well as the increased rolling loads encountered during hot rolling of Nb containing steels.

Multi-Phase Steels

Multi-phase steels, also sometimes referred to as complex-phase steels, are high strength steels characterized by high tensile and yield strength combined with moderate elongation. Sometimes an added feature of these steels is high stretch flangeability generally measured by hole expansion tests. The microstructures of these steels generally constitute several phases such as ferrite, pearlite, bainite and tempered martensite.

Nb is added to these steels to achieve strengthening by precipitation hardening as well as by refined grain size through solute drag effects. In addition, Nb enhances bainite microstructure for strength and/or stretch flangeability.

Typical composition and properties of the most common steel, 590 HY, is given in Table IV.

Table IV. Typical composition and microstructure of a representative multi-phase steel containing Nb.

Typical Compositions (Wt. %)

	C	Mn	P	Al	**Nb**	Si
590 R (HY)	0.13	1.6	0.02 max	0.04	**0.037**	0.10

Typical Properties

	Tensile Strength (MPa)	Yield Strength (MPa)	Total Elongation (%)
590 R(HY)	620	505	26.0

For a more complete work on 590 MPa steels, the reader is referred to reference [15].

Dual Phase Steels

In dual phase steels, the major role played by Nb is the generation of a finer hot rolled grain size and consequently a final microstructure. This, in turn, leads to two benefits. First, it is believed that a finer microstructure results in lower variability of properties. This is important, as property variability is an ongoing concern in dual phase steels. Second, a finer grain size reduces banding resulting from the invariable high Mn content in these steels. Reduced banding contributes to improved bendability, which is important for the manufacture of certain parts. A typical such product is DP 980 HB (980 MPa min. tensile strength, high bendability).

Typical mechanical properties and microstructure of this product are shown in Table V and Figure 7, respectively.

Table V. Target and typical properties of a dual phase high bendability steel.

	Tensile Strength, MPa	Yield Strength, MPa	Uniform Elongation	Total Elongation	Yield Point Elongation	Bend, 90°, (r/t)
Properties	1030	650	8	13	0	1.5
Target	>980	580-730		>8		<2.5

For a detailed understanding of 980 MPa dual phase steels, please refer to reference [16].

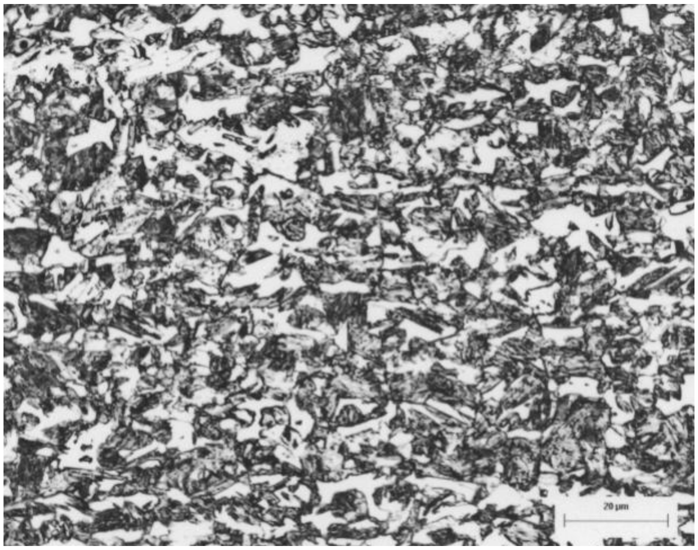

Figure 7. Typical microstructure of a dual phase high bendability steel.

TRIP Steels

Transformation Induced Plasticity (TRIP) steels, as is well known, are steels with a ferrite, bainite and retained austenite microstructure. As a result, these steels offer a combination of high strength with excellent formability in terms of both elongation and n value. This high level of energy absorbing capacity is ideal for certain crash resistant parts. At the same time, the high formability allows for manufacture of complex parts.

The major positive effects of Nb addition in TRIP steels are:

- Nb increases the stability of austenite; this contributes to the presence of retained austenite in the final microstructure.

- Nb refines the hot rolled grain structure and thus the final microstructure. This improves the strength as well as other aspects of performance.
- Nb provides some precipitation hardening contributing to strengthening of the product.
- Nb enhances the bainite reaction, particularly at temperatures of galvannealing. This is clearly shown in Figure 8 [16] below. As a result of increased bainite formation at a faster rate, it is possible to enrich the remaining austenite with carbon and stabilizing it. As a result, it is retained as austenite in the final structure, even at the relatively low times of holding during galvannealing in a continuous line.
- Nb increases bake hardenability [18].
- Nb has no deleterious effects on the galvannealing reaction in these steels.

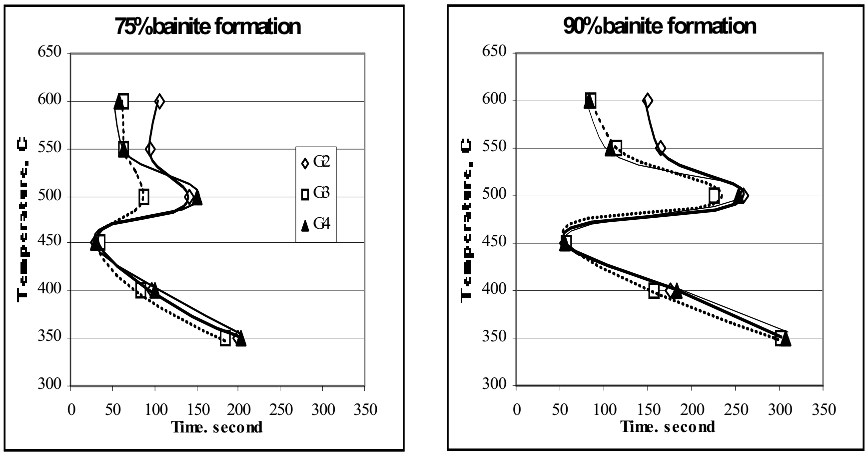

Figure 8. Effect of Nb on bainite transformation in a TRIP steel.

There is one issue with Nb-containing TRIP steels, however, which needs to be discussed. Under certain conditions, depending on the capability of a certain facility, hot rolling of Nb-containing TRIP steels could pose a challenge. The first reason is that Nb increases the hot deformation resistance of TRIP steels [19] and because TRIP steels have a high deformation resistance to start with, Nb additions further exacerbates the problem. As a result, the maximum width and/or gauge, which can be manufactured, may be limited. The second reason for concern is the unusual variation in force as the temperature of hot rolling decreases with progression of rolling. This has been well documented by Skolly and Poliak [20]. One typical curve is shown in Figure 9.

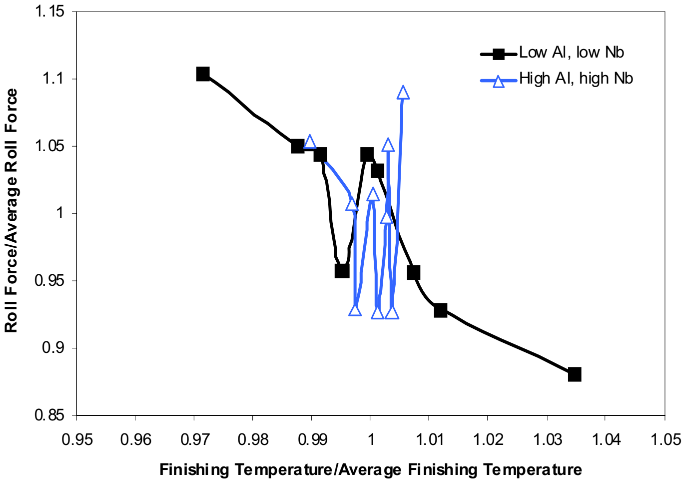

Figure 9. Force variation in hot rolling of a high Al TRIP steel containing Nb.

Because of the force instability, conventional control models do not work and there is risk of cobbling. Thus, these steels have to be carefully modeled and hot-rolled for ease of manufacturing.

The typical composition and properties of a representative TRIP steel with 590 MPa tensile strength is show in Table VI.

Table VI. Typical composition and properties of a TRIP 590 steel containing Nb.

Typical Compositions (Wt. %)

	C	Mn	Si	Al	**Nb**
590 TRIP	0.12/0.17	1.2/1.7	0.2/0.6	**0.7/1.3**	**0.02/0.04**

Typical Properties

	Tensile Strength (MPa)	Yield Strength (MPa)	Total Elongation (%)
590 TRIP	610	410	35

Summary

The above brief review of the role of Nb in steels shows that Nb has several major effects on the microstructure and properties in steels. Nb increases the strength of steel through grain refinement, precipitation hardening and through phase stabilization. It reduces anisotropy of properties producing a more isotropic steel. It improves the galvannealing characteristics and produces a more uniform galvanneal coating. It also stabilizes austenite and enhances the bainite reaction, both of which can be useful for production of certain advanced high strength steels. Care must be taken in hot rolling of Nb-containing steels because of its effect on deformation resistance and stability of rolling forces. Overall, Nb is a useful alloying addition for the production of advanced high strength steels for automotive applications.

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