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FERRITIC STAINLESS STEELS WITH IMPROVED STRETCH-FORMING CHARACTERISTICS
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FIG. 1

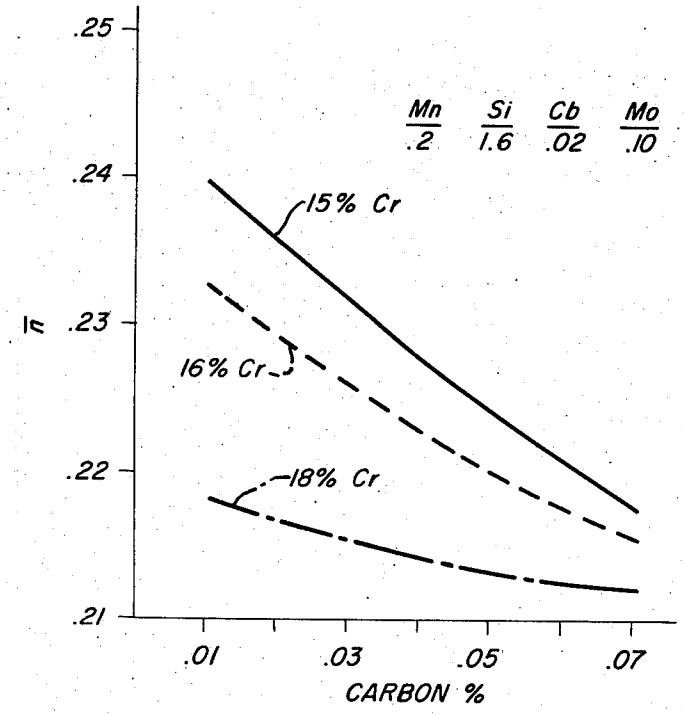
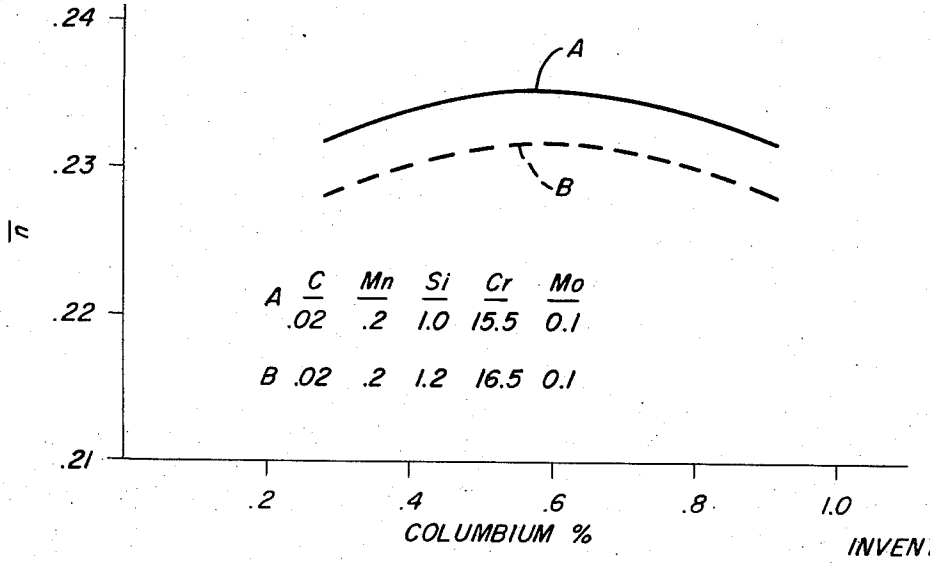


FIG. 2



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FERRITIC STAINLESS STEELS WITH IMPROVED STRETCH-FORMING CHARACTERISTICS

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ABSTRACT OF THE DISCLOSURE

A method for improving the stretch forming characteristics of ferritic stainless steels. A complex equation shows the interrelation of the various alloying elements. Within the compositional range similar to that of Type 430 steel, the stretchability, as represented by $\bar{n}$ value, may be increased by decreasing the C, Mn, and Cr and increasing the Si. Further enhancement may be achieved by additions of Cb, with a maximum at 0.6% Cb. Mo is shown to be detrimental to high $\bar{n}$ value, and if employed for its corrosion enhancement, the C and Mn must be further decreased.

This invention relates in general to ferritic stainless steel, sheet and strip and more particularly to annealed ferritic stainless steel with good stretchability.

Over the years, there has been a gradual but a continual growth in the use of stainless steel sheet and strip in applications requiring forming. This growth is expected to increase as consumers become more quality conscious and demand household and industrial goods made from stainless steels. For many of these applications, the ferritic stainless steels as typified by AISI Type 430 stainless steels are used.

In addition to their enhanced corrosion resistance, the ferritic stainless steels polish to a very high luster and are therefore employed in applications where appearance is important. Type 430 stainless steel is used in applications requiring a moderate degree of forming, such as kitchen sinks and luggage trim. For applications requiring somewhat better corrosion resistance than Type 430, such as automotive trim and hubcaps (which are subject to chloride-containing environments) proprietary Types 430–Mo (434) or 430–Mo-Cb (436) are employed. For applications involving severe stretch forming and in which the occurrence of ridging would be detrimental to appearance, columbium modified Type 430 (435) is often used because of the enhanced resistance to ridging supplied by columbium (U.S. Pat. 2,965,479). Ridging is an undesirable surface condition that occurs parallel to the direction of rolling and appears as narrow, raised areas, similar to corrugations on the surface of the sheet. One drawback to the use of the ferritic stainless steels in forming operations is their poor formability, particularly their stretch-forming characteristics, in comparison to low carbon steel, which is generally used for forming operations.

For many metals, the shape of the plastic portion of the tension stress-strain curve expressed in terms of true stress and true strain may be closely described by the Ludwik equation $\sigma=Ke^n$. In this equation, it is n, the strain-

hardening exponent, that is the measure of the ability of a metal to resist localized straining and thus withstand complex non-uniform deformation. If the uniform elongation is expressed as true strain, it is numerically equal to n. A metal with a low value of n will undergo localized straining early in a stretching process and failure will occur much before uniform straining has occurred. On the other hand, a metal that has a high n will tend to strain uniformly, even under non-uniform stress conditions. Thus, for good stretchability, a high strain-hardening exponent, n, is desirable. In fact, rather small changes in the average n value have a marked effect on the stretch-forming characteristics or stretchability of steel. The average n value, $\bar{n}$, is defined as follows:

$$\bar{n}=\frac{n_0+2n_{45}+n_{90}}{4}$$

where 0, 45, and 90 are degrees from the rolling direction of sheet or strip.

The influence of even small changes in $\bar{n}$, on the ability to withstand non-uniform deformation and thereby resist failure, will be better appreciated by reference to the table below. The part involved is a low carbon steel door panel, the production of which requires an operation which is predominantly stretch-forming.

TABLE I

Steel	$\bar{n}$	Number of blanks formed	Percent scrap (failure)
1	0.202	207	10.0
	0.232	193	0
2	0.209	198	5.0
	0.219	195	1.5

It may be seen, that as the $\bar{n}$ value increased just slightly, the percentage of scrap parts produced decreased rather markedly. Generally, the class of ferritic stainless steels under consideration, exhibit $\bar{n}$ values less than 0.21. For example, the $\bar{n}$ values of some typical ferritic stainless stels, when tested as 0.040 inch thick annealed sheet were:

		Composition (in percent by weight)							
Type	$\bar{n}$	C	Mn	P	S	Si	Cr	Mo	Cb
430	.188	0.096	0.54	0.018	0.012	0.54	16.9	0.11	0.03
434	.184	0.094	0.50	0.017	0.011	0.56	16.9	1.06	0.02
435	.196	0.096	0.55	0.017	0.013	0.49	17.1	0.12	0.50
436	.181	0.100	0.52	0.017	0.012	0.61	17.2	1.02	0.47

It is, therefore, an object of this invention to provide annealed ferritic stainless steels with good formability, and particularly enhanced stretchability.

It is another object of this invention to provide a method for tailoring the stretchability properties of ferritic stainless steels for such applications as automobile and luggage trim.

It is a further object of this invention to provide a ferritic stainless steel with an average strain-hardening exponent, $\bar{n}$, of at least 0.23, when produced as annealed sheet.

FIG. 1 shows the interaction of chromium and carbon and their effect on $\bar{n}$ value, and

FIG. 2 shows the beneficial effect of columbium on increasing $\bar{n}$ value.

Shown in Table II are the compositions of the 34 steels that were prepared as induction-furnace heats during the development of the new steel. These steels can also be made by conventional practice in an electric furnace. All heats were melted under an argon cover and cast into 3-inch-thick by 8-inch-wide by 14-inch-high slab-type molds for this study. The surfaces of each slab-type ingot were conditioned by machining. The slabs were hot rolled at 2150° F. to 0.160-inch-thick strip. The strip-finishing temperature was about 1500° F. Hot-rolled strip from each heat was given a simulated box anneal at 1450° F. for six hours and furnace cooled. The annealed strip was shot-blasted to remove scale and then cold-rolled to 0.080-inch-thick strip. The cold-rolled strip was then annealed in salt for 15 seconds at 1450° F. and air cooled. The salt-annealed 0.080-inch-thick strip was cleaned with a detergent and cold-rolled to 0.040-inch-thick strip, which was again annealed in salt for two minutes at 1450° F. and air cooled. These latter annealing treatments simulated commercial continuous annealing. The processing cycle from ingot to cold-rolled and annealed strip simulated closely that which is given commercially produced Type 430 stainless steels.

From the cold-rolled and annealed 0.040-inch-thick strip from each of the 34 heats, six tension-test specimen blanks were sheared. Two blanks were sheared parallel to the rolling direction (longitudinal), two blanks were sheared transverse to the rolling direction, and two blanks were sheared at 45 degrees from the rolling direction (diagonal). These blanks were then machined into formability test specimens, which were tension tested at room temperature and their n values determined. The $\bar{n}$ values of each steel were then calculated. The n values in the longitudinal, transverse, and diagonal directions for the steels investigated are shown in Table III. Also shown in this table are the $\bar{n}$ values for these steels.

TABLE II.—COMPOSITIONS OF FERRITIC STAINLESS STEELS INVESTIGATED, IN WEIGHT PERCENT

Heat Number	C	Mn	Si	Cr	Mo	Cb
V9156-3	0.10	0.52	0.61	17.2	1.02	0.47
V9157-2	0.099	0.53	0.56	18.9	0.59	0.50
V9158-2	0.054	0.74	0.36	17.9	0.35	0.26
V9159-1	0.053	0.34	0.66	17.8	0.35	0.26
V9160-1	0.096	0.16	0.51	17.0	0.59	0.50
V9161-1	0.095	0.51	0.55	17.0	0.60	0.50
V9162-2	0.15	0.33	0.38	16.4	0.80	0.25
V9163-1	0.10	0.51	0.53	16.9	0.60	0.96
V9164-1	0.11	0.53	0.52	17.1	0.59	0.51
V9165-1	0.060	0.70	0.41	16.0	0.33	0.72
V9166-1	0.15	0.70	0.65	16.0	0.83	0.28
V9167-1	0.059	0.35	0.70	17.9	0.83	0.75
V9168-1	0.11	0.52	0.50	17.1	0.60	0.50
V9169-1	0.096	0.55	0.54	17.1	0.58	0.028
V9170-1	0.051	0.72	0.41	17.8	0.83	0.71
V9171-1	0.096	0.55	0.49	17.1	0.12	0.50
V9172-1	0.096	0.98	0.50	17.1	0.58	0.50
V9173-1	0.049	0.70	0.40	15.9	0.79	0.26
V9174-1	0.098	0.55	0.55	17.1	0.60	0.52
V9175-1	0.014	0.47	0.54	17.3	0.60	0.52
V9176-1	0.15	0.72	0.72	18.6	0.82	0.78
V9177-1	0.14	0.36	0.42	16.2	0.35	0.76
V9178-1	0.10	0.53	0.94	17.1	0.60	0.53
V9179-3	0.16	0.54	0.40	17.0	0.59	0.48
V9180-1	0.14	0.73	0.79	18.0	0.32	0.25
V9181-1	0.096	0.56	0.55	17.0	0.57	0.48
V9182-1	0.13	0.36	0.37	18.0	0.32	0.24
V9183-1	0.096	0.52	0.52	15.2	0.57	0.48
V9184-1	0.14	0.71	0.77	16.2	0.32	0.73
V9185-1	0.050	0.36	0.80	16.2	0.33	0.75
V9186-1	0.14	0.35	0.36	17.9	0.80	0.70
V9187-1	0.049	0.34	0.74	16.2	9.82	0.26
V9188-1	0.093	0.55	0.23	17.0	0.57	0.48
V9189-1	0.094	0.54	0.55	17.2	0.58	0.49

NOTE.—The above analysis reports only those elements which bear a relation to the instant invention. The various heats also contained:
P=0.012-0.018.
S=0.004-0.014
Ni=0.24-0.028.
Cu=0.042-0.058.
N=0.046-0.060.

TABLE III.—THE LONGITUDINAL, DIAGONAL, TRANSVERSE, AND AVERAGE STRAIN-HARDENING EXPONENTS OF THE FERRITIC STAINLESS STEELS INVESTIGATED

Heat number	n_0	n_{45}	n_{90}	$\bar{n}$
V9156-3	0.178	0.183	0.178	0.181
V9157-2	0.192	0.201	0.194	0.197
V9158-2	0.187	0.191	0.189	0.190
V9159-1	0.195	0.199	0.194	0.197
V9160-1	0.195	0.199	0.181	0.194
V9161-1	0.191	0.195	0.178	0.190
V9162-2	0.179	0.181	0.180	0.180
V9163-1	0.195	0.180	0.189	0.186
V9164-1	0.189	0.184	0.178	0.184
V9165-1	0.200	0.202	0.205	0.202
V9166-1	0.181	0.184	0.176	0.181
V9167-1	0.199	0.192	0.187	0.193
V9168-1	0.191	0.187	0.189	0.189
V9169-1	0.177	0.193	0.165	0.182
V9170-1	0.184	0.179	0.166	0.177
V9171-1	0.197	0.194	0.198	0.196
V9172-1	0.184	0.191	0.184	0.188
V9173-1	0.197	0.182	0.190	0.188
V9174-1	0.195	0.188	0.198	0.192
V9175-1	0.197	0.208	0.210	0.206
V9176-1	0.193	0.190	0.189	0.191
V9177-1	0.197	0.197	0.189	0.195
V9178-1	0.200	0.201	0.193	0.199
V9179-3	0.187	0.182	0.190	0.185
V9180-1	0.223	0.185	0.182	0.194
V9181-1	0.194	0.196	0.184	0.193
V9182-1	0.194	0.187	0.220	0.197
V9183-1	0.185	0.192	0.175	0.186
V9184-1	0.191	0.196	0.187	0.193
V9185-1	0.213	0.215	0.207	0.213
V9186-1	0.194	0.201	0.189	0.196
V9187-1	0.200	0.201	0.194	0.199
V9188-1	0.196	0.194	0.191	0.194
V9189-1	0.203	0.209	0.198	0.205

Analysis of the $\bar{n}$ values in Table III indicated that a relation existed between $\bar{n}$ and the compositions of the steels investigated. It was found that the relation could be expressed by the following equation (all percentages are by weight):

$$\bar{n}=0.199-0.062\ (\text{percent C})-0.016\ (\text{percent Mn})+0.014\ (\text{percent Si})+0.0005\ (\text{percent Cr})-0.021\ (\text{percent Mo})+0.0067\ (\text{percent Cb})+1.12\ (\text{percent C}-0.097)^2-0.033\ (\text{percent Cb}-0.50)^2+0.089\ (\text{percent C}-0.097)\ (\text{percent Cr}-17.05)$$

Inspection of this equation indicates the complexity of the problem of attempting to tailor the stretchability of the hereinabove mentioned ferritic stainless steels. Note, for example, the quadratic effects of carbon and columbium and the interactions between carbon and chromium. These effects complicate the relation between these elements and $\bar{n}$. However, with the aid of this equation, it is possible to modify Type 430, 434, 435, and 436 steels so that their $\bar{n}$ values may be decidedly and unexpectedly increased.

The applicability of this equation to each of these steels, will be demonstrated individually.

Type 430—The AISI range for this steel is:

	Percent
C	[1] 0.12
Mn	[1] 1.0
Si	[1] 1.0
P	[1] 0.040
S	[1] 0.030
Cr	14.0–18.0

[1] Maximum.

In this steel, columbium and molybdenum are not added as an alloy addition, and are present only as incidental steel-making impurities, generally in amounts of about 0.02 and 0.10 percent, respectively.

From the standpoint of $\bar{n}$ value alone, it is beneficial to increase Si to above that of the AISI specifications.

However, silicon is known to be detrimental to both hot workability and weldability and should therefore be limited to less than about 2.0%. In applications in which severe bending will be encountered, it is desirable to even further limit the silicon content, thereby avoiding the detrimental effect that silicate inclusions have on bending performance. However, in order to maintain practical ranges for carbon and chromium, (i.e., those attainable by normal commercial melting practices, without the need for special melting procedures and controls) at least about 1.0% Si is desirable for providing a high $\bar{n}$ value.

The critical effect of decreasing the carbon content may be seen by reference to FIG. 1, which shows the predicted effect of carbon on $\bar{n}$ value for three levels of chromium. Thus, when chromium is within the lower end of the range, i.e., 15 to 16%, a minimum $\bar{n}$ value of 0.23 may be achieved by decreasing the carbon to below about 0.035% and 0.02% respectively, whereas, at high Cr levels, the effect of lowering the C content on $\bar{n}$ value is less significant. Thus, at the 18% Cr level, while some increase in $\bar{n}$ is achieved by lowering the carbon content, the rate of increase in $\bar{n}$ is too small to achieve a significant increase in $\bar{n}$ value. It should be recognized, that even lower Mn or higher Si in the steels under consideration, would permit the use of somewhat higher carbon and chromium contents. Low carbon levels, in addition to their effect on $\bar{n}$ values, are also desirable for minimizing bend failures. Because many stretch-formed parts are often subjected to severe bending operations, the ability to make such bends is also important. Inspection of the $\bar{n}$ equation shows the desirability of keeping Mn at low levels. In a composition in which Cr and C are kept at the lower end of the range (e.g. 15.0 and 0.1% respectively) and Si at the higher end of its range (e.g. approaching 2.0%), up to about 0.4% Mn can be tolerated.

Thus, a modified Type 430 steel with good formability and particularly good stretchability may be obtained in a composition comprising:

C	[1] 0.035
Mn	[1] 0.4
Si	1.0–2.0
Cr	14.5–16.5

[1] Maximum.

wherein the $\bar{n}$ value may be increased by either

(a) employing C at the low end of the range, or
(b) employing Mn at the low end of the range, or
(c) employing Cr at the low end of the range, or
(d) employing Si at the high end of the range,

or a combination of any two or more of the above expedients.

Type 430-Cb (435).—These steels contain up to about 1.0% Cb as a purposeful alloy addition. FIG. 2 shows the predicted effect of columbium on $\bar{n}$ for two steels in which the Cr and Si contents have been varied. It may be seen that in both steels a maximum $\bar{n}$ *is a*ttained at about 0.6 percent columbium. This is a reflection of the quadratic effect of columbium as shown in the equation. It is also noteworthy that within the contemplated range, even as little as 0.1% Cb is beneficial in increasing the $\bar{n}$ value. Therefore, if Cb is employed in the preferred range of 0.4 to 0.8 percent, the permissible range of C, Cr, and Mn for attaining $\bar{n}$ values of about 0.23 may thus be increased. For the same reason, it is no longer necessary to impose a 1.0 percent lower limit on the amount of Si, since by judicious control of the other elements, an $\bar{n}$ value greater than 0.23 could be attained with as little as 0.1% Si.

Therefore, a modified Type 435 stainless steel with resistance to ridging and particularly good stretchability may be obtained in a composition comprising

C	Trace to 0.05%.
Mn	Trace to 0.5%.
Si	0.1 to 2.00%.
Cr	14.5 to 18.0%.
Cb	0.4 to 0.8%.

wherein the $\bar{n}$ value may be increased by either

(a) employing C at the lower end of the range, or
(b) employing Mn at the lower end of the range, or
(c) employing Cr at the lower end of the range, or
(d) employing Si at the higher end of the range, or
(e) employing Cb near the middle of the range,

or a combination of any two or more of these aforesaid expedients.

Type 430-Mo (434).—Inspection of the equation shows that Mo additions are detrimental to high $\bar{n}$ values. Therefore in a steel, in which from about 0.5% to about 1.0% Mo is added to achieve corrosion resistance, it is necessary to employ C, Mn, and Cr at even lower levels (i.e. 0.02%, 0.2% and 16.0% respectively) than for a basic Type 430 steel. Likewise, a minimum of about 1.4% Si is required to provide an $\bar{n}$ value of about 0.23.

Type 430 Mo-Cb (436).—It has been shown above, that within the ranges of Cb (0.4–0.8 percent) and Mo (.5–1.0 percent) under consideration, that these elements have counterbalancing effects on $\bar{n}$ value. Thus, within these ranges, a ferritic stainless steel with enhanced corrosion resistance (provided by the Mo), resistance to ridging (due to the Cb) and particularly good stretchability may be achieved by employing a range of C (0.035 max.), Mn (0.4 max.), Si (1.0–2.0) and Cr (14.5–16.5) substantially the same as that of Type 430 steel.

I claim:

1. A method for enhancing the stretch-forming characteristics of ferritic stainless steel sheet within the range consisting of:

C	Trace to 0.12%.
Mn	Trace to 1.0%.
Si	Trace to 2.0%.
Cr	14.5 to 18.0%.
Mo	Trace to 1.0%.
Cb	Do.

balance Fe and incidental residual impurities, which comprises combining the above elements in proportions which satisfy the equation

$$0.031 \leq -.062\,(\text{percent C}) - 0.016\,(\text{percent Mn}) + 0.014\,(\text{percent Si}) + 0.0005\,(\text{percent Cr}) - 0.021\,(\text{percent Mo}) + 0.0067\,(\text{percent Cb}) + 1.12\,(\text{percent C} - 0.097)^2 - 0.033\,(\text{percent Cb} - 0.50)^2 + 0.089\,(\text{percent C} - 0.097)\,(\text{percent Cr} - 17.05)$$

to achieve an $\bar{n}$ value equal to or greater than 0.23.

2. The method of claim 1, wherein Cb and Mo are only present in normal residual amounts, which further comprises employing less than 0.035% C, less than 0.4% Mn, less than 16.5% Cr and more than 1.0% Si.

3. The method of claim 1, wherein about 0.4 to 0.8% Cb is employed to further enhance the $\bar{n}$ value.

4. An annealed, ferritic stainless steel sheet, with enhanced stretchability, as represented by an $\bar{n}$ value greater than 0.23, consisting of

C	Trace to 0.12%.
Mn	Trace to 1.0%.
Si	Trace to 2.0%.
Cr	14.5 to 18.0%.
Mo	Trace to 1.0%.
Cb	Do.

balance Fe and incidental residual impurities, in proportions which satisfy the equation:

$$0.031 \leq -0.062 \text{ (percent C)} - 0.016 \text{ (percent Mn)} + 0.014 \text{ (percent Si)} + 0.0005 \text{ (percent Cr)} - 0.021 \text{ (percent Mo)} + 0.0067 \text{ (percent Cb)} + 1.12 \text{ (percent C} - 0.097)^2 - 0.033 \text{ (percent Cb} - 0.50)^2 + 0.089 \text{ (percent C} - 0.097) \text{ (percent Cr} - 17.05)$$

5. The steel of claim 4, wherein Cb and Mo are only present in residual amounts and consisting of

C	Trace to 0.035%.
Mn	Trace to 0.4%.
Cr	14.5 to 16.5%.
Si	1.0 to 2.0%.

balance Fe and incidental residual impurities.

6. The steel of claim 4, wherein Mo is only present in residual amounts and consisting of

C	Trace to 0.05%.
Mn	Trace to 0.5%.
Cr	14.5 to 18.0%.
Si	0.1 to 2.0%.
Cb	0.4 to 0.8%.

balance Fe and incidental residual impurities.

7. The steel of claim 4, wherein Cb is only present in residual amounts and consisting of

C	Trace to 0.02%.
Mn	Trace to 0.2%.
Cr	14.5 to 16.0%.
Si	1.4 to 2.0%.
Mo	0.4 to 1.0%.

balance Fe and incidental residual impurities.

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