Quantification of the Influence of Factors on Abnormal Austenite Grain Growth in Carburized Steel Parts for Drivetrain

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Abstract

Carburized components produced via cold forging may exhibit abnormal austenite grain growth, resulting in diminished mechanical strength. While the qualitative factors influencing this phenomenon are recognized, their relative degrees of impact remain poorly defined. Consequently, this study utilizes test specimens simulating the component manufacturing process to experimentally elucidate the relationship between specific influencing factors and the resulting austenite grain size following carburization.(1)

1. Introduction

Carburizing, quenching, and tempering (hereinafter referred to as “carburization”) is a widely utilized heat-treatment method for automotive drivetrain components to achieve requisite wear resistance and fatigue strength. However, reports indicate that the abnormal grain growth (G.G.) of austenite crystal grains during this heat-treatment process significantly reduces the mechanical properties of the components, thereby adversely affecting product life and reliability.(2) Previous studies have identified factors related to the occurrence of abnormal G.G., specifically citing precipitate distribution, strain during plastic forming, and heat treatment temperature conditions as primary factors.(3) (4) However, the interaction between these factors and their respective degrees of impact on G.G. remain inadequately understood in many instances.

Test pieces simulating cold-formed carburized components (hereinafter referred to as “TP”) were employed in this study to identify the factors affecting the occurrence of G.G. and to quantify the degree of their influence.

2. Objective

Previous investigations on the occurrence of G.G. evaluated the influence of individual parameters by isolating each variable.(5) However, actual component manufacturing involves a multitude of concurrent parameters affecting G.G. Therefore, to effectively suppress G.G., it is essential to comprehensively investigate these variables and to quantitatively evaluate the specific impact of each parameter on G.G.

Furthermore, even when the influence of a factor is quantified, its utility is limited if the factor remains uncontrollable within the component manufacturing process.

Therefore, this study aims to identify parameters that allow for direct feedback into the manufacturing conditions and to quantitatively evaluate their respective impacts.

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3. Methodology

G.G. is a phenomenon resulting from transformations in metallic microstructures. Accordingly, factors related to the mechanism of G.G. and those influencing its occurrence were systematically categorized relative to each stage of microstructural change. Specifically, the analysis was divided into the following four steps, as illustrated in Fig. 1:

STEP 1: Relationship between G.G. and microstructure following carburization,
STEP 2: Relationship between microstructures after carburization and after cold forming,
STEP 3: Relationship between the cold-formed microstructure and the initial material microstructure and manufacturing conditions, and
STEP 4: Relationship between G.G. and parameters controllable during manufacturing.

In each step, a multivariate analysis was performed to examine the relationships between the objective and explanatory variables, allowing for the extraction of highly correlated parameters.

Finally, in STEP 4, the relationships between G.G. and parameters controllable within the manufacturing process were quantified via multivariate analysis.

This methodology facilitates a sequential analysis of the influence of microstructural changes across intermediate processes. Consequently, this approach provides a clear understanding of the degree of impact on G.G. exerted by controllable manufacturing parameters such as material properties and component manufacturing conditions.

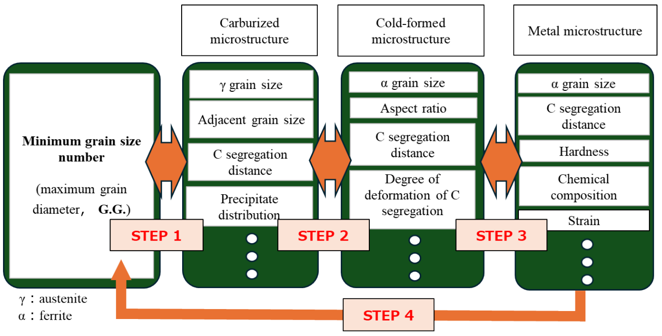


Fig. 1 Extraction and quantification procedure for G.G. influence parameters

4. Parameter extraction approach

4.1 Mechanism of G.G. occurrence

G.G. is a phenomenon that occurs to reduce the energy differential between adjacent grains, with grain boundary energy serving as the primary driving force.

However, the mechanism of G.G. occurrence depends not only on the grain boundary energy, but also on several extrinsic factors, including strain energy, thermal energy, and the G.G. inhibition energy provided by precipitates. To account for these combined effects, the influencing parameters associated with each energy factor were systematically extracted in this study.

4.2 Parameters related to grain boundary energy

Grain boundary energy, which is determined by crystallographic factors, is the intrinsic energy of the grain boundary itself.

The G.G. occurring during the carburization process is a phenomenon that mitigates the energy gradient resulting from differences in the grain boundary curvature. Therefore, under constant strain and thermal energy conditions, the occurrence of G.G. is primarily attributed to the grain size differential between adjacent crystals. From this perspective, parameters related to grain size and its distribution within the metallic microstructure were extracted in this study.

4.3 Parameters related to strain energy

Strain energy is the energy stored within a material during plastic deformation processes, such as cold forming. Strain energy directly affects the recrystallization and phase transformation temperatures during carburization and is an important factor controlling the behavior of G.G. Accordingly, parameters related to cold forming conditions and the resulting cold-formed microstructure were extracted in this study.

4.4 Parameters related to thermal energy

Thermal energy is the energy imparted to a material during heat treatment processes such as carburization. The magnitude of this energy significantly influences the growth behavior of crystal grains following recrystallization and phase transformation. To quantitatively evaluate this effect, the temperature conditions during carburization were extracted as critical parameters in this study.

4.5 Carbon concentration distribution

Variations in the carbon concentration in a material induce changes in the transformation temperature of the metallic microstructure and the formability of the material. Specifically, during cold forming processes, ferrite grains (hereinafter referred to as “α grains”) situated around carbon segregation sites (hereinafter referred to as “C segregation sites”) tend to exhibit greater deformation and accumulate higher strain energy than those in regions devoid of C segregation. Therefore, parameters related to the microstructural properties surrounding C segregation sites were extracted in this study.

4.6 Parameters related to grain-growth inhibition energy

Fine dispersion of precipitates at grain boundaries can effectively suppress G.G. Precipitates with diameters of 20 nm or less are reportedly effective in suppressing G.G.(6) Accordingly, parameters related to the precipitate size distribution were extracted in this study.

Following these principles, the various energy factors involved in the mechanism of G.G. occurrence were systematically categorized, and the parameters influencing each energy factor were comprehensively extracted (Table 1).

Table 1 Extracted parameters

Material and forming parameters	Hardness
	α particle size No. ave.
	α particle size No. σ
	C segregation width ave.
	C segregation width σ
	C segregation width ave.-σ
	C segregation interval ave.
	C segregation interval σ
	C segregation interval ave.-σ
	Chemical composition
	Shear strain
	Equivalent strain
Post-cold forming and carburization parameters	α particle size No. ave. in C segregation
	α particle size No. σ in C segregation
	α particle size No. ave.
	α particle Size No. σ
	Aspect ratio of α particles
	P-F angle
	L×Θ
	T×Movement distance
	Hardness ×C segregation movement distance
	C segregation interval ave.
	C segregation interval σ
	C segregation interval ave.-σ
	C segregation width ave.
	C segregation width σ
	C segregation width ave.-σ
	Carburizing temperature
Post-carburization parameters	γ particle size No. ave.
	γ particle size No. σ
	γ particle size area ratio (No. ≤ 5)
	γ particle size area ratio (No. ≥ 10)
	Area ratio of particle size No. ≤ 5 near C segregation
	Area ratio of particle size No. ≥ 10 near C segregation
	γ particle size No. ave around maximum γ particle
	γ particle size No. σ around maximum γ particle
	Distance from maximum γ particle to C segregation
	C segregation interval
	C segregation width
	Quantity of fine precipitates
	Precipitate size ave.

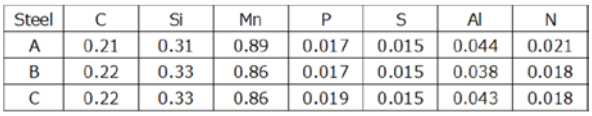
5. Experimental methods

Experiments were conducted in this study using TPs that simulated the actual component manufacturing process to comprehensively investigate the variations in the metallic microstructure during the manufacturing process.

5.1 Specimen material

SCr420, as specified in the JIS G 4053 standard, was used as the specimen material. Three material production lots were used in the experiments to vary the states of the precipitates (Table 2).

Table 2 Chemical composition (mass%)



Steel	C	Si	Mn	P	S	Al	N
A	0.21	0.31	0.89	0.017	0.015	0.044	0.021
B	0.22	0.33	0.86	0.017	0.015	0.038	0.018
C	0.22	0.33	0.86	0.019	0.015	0.043	0.018

5.2 Material microstructure

As described in Section 4.5, the material microstructures influences the strain applied to α grains during cold forming. TPs with distinct metallic microstructures (Fig. 3) were produced by first machining the specimens into cylindrical ϕ8 × 12 mm TPs, followed by heating them to the γ single-phase region, and subsequently cooling them at varied rates (Fig. 2).

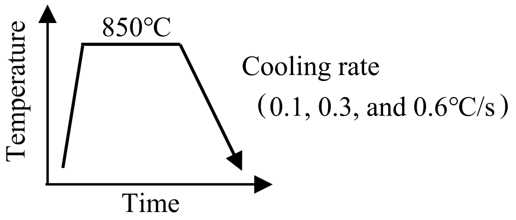


Fig. 2 Conditions for controlled microstructures

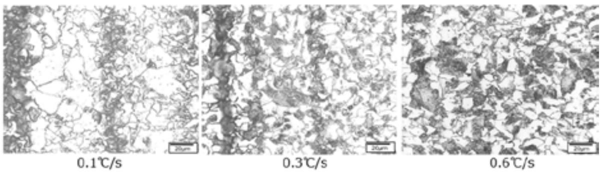


Fig. 3 Examples of controlled microstructures

5.3 Addition of strain energy owing to cold forming

Cold forming was performed via simple compression of the cylindrical TPs. The applied effective strain and shear strain were determined via finite element analysis. Furthermore, changes in the metallic microstructure relative to the varied strain distributions within the TPs were also investigated (Fig. 4).

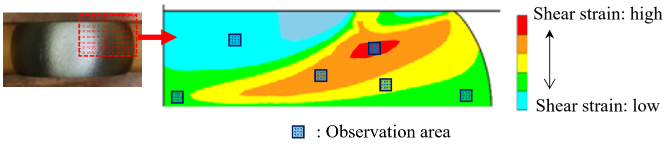


Fig. 4 Finite element analysis of strain distribution during compression testing

5.4 Addition of thermal energy by carburization

Three carburization temperatures were used in this study, namely, 950, 970, and 1,000°C. After holding the specimens at each temperature for a prescribed time, the specimens were oil quenched (Fig. 5).

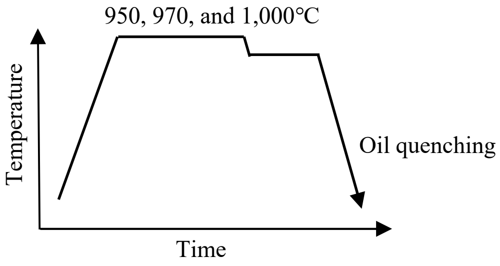


Fig. 5 Carburization Conditions employed in the study

5.5 Occurrence of G.G. and its relationship with each parameter

The metallic microstructure at each stage of the process was examined, and the parameters listed in Table 1 were quantified. In this study, the grain size of the metallic microstructure was determined by measuring the crystal grain size number (hereinafter referred to as "grain size No.") in accordance with the JIS G 0551 standard. This standard indicates that a larger grain size No. represents a finer crystalline grain size (hereinafter referred to as "grain size").

The metallic microstructure was examined, and factors related to the microstructure were quantified. This data was used to perform a multivariate analysis to evaluate the relationships between the objective and explanatory variables for each step illustrated in Fig. 1.

6. Results

6.1 Factors influencing G.G. during intermediate processes

6.1.1 Relationship between G.G. and the microstructure after carburization (STEP 1)

As previously reported, G.G. is highly correlated with the metallic microstructure following carburization (Table 3, Fig. 6). Significant G.G. was observed near the periphery of the C segregation (Fig. 7), where the variation in the γ grain size was substantial. This indicates that G.G. was strongly influenced by the factors associated with the carburization process.

Table 3 G.G. parameters of carburized microstructure

Objective variable name	R²
Maximum γ grain size number	0.78
Explanatory variable name	Standardized regression coefficient
Distance to C segregation in maximum γ grain	0.50
Area ratio of γ grains with size number < 5 near the C segregation	-0.31
Average size number of the grains surrounding the maximum γ grain	-0.24
Amount of AlN fine precipitates	-0.04
Average diameter of AlN precipitates	0.00

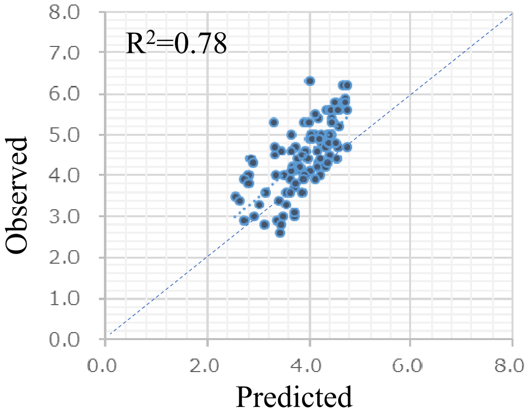


Fig. 6 Multivariate analysis results using carburized metal microstructure parameters (STEP 1)

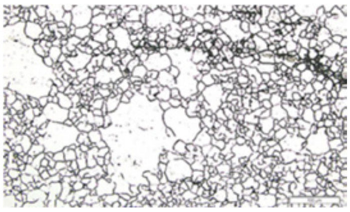


Fig. 7 An example of post-carburizing microstructure where G.G. occurs

6.1.2 Relationship between the post-carburization microstructure and parameters after cold forming (STEP 2)

Among the parameters extracted in Section 6.1.1, those demonstrating strong correlation with the post-carburization microstructure include the average α grain size No. of the material and its variation, grain size No. following cold forming, distance to the C segregation, and deformation angle near the C segregation, the latter representing the crystal deformation degree. These were identified as the dominant parameters (Table 4).

The results indicate that the post-carburization microstructure influencing G.G. is related to both the inter-granular energy following cold forming and the strain energy accumulated during the cold forming process.

Table 4 Relationship between post-carburizing microstructure and parameters after cold forming

G.G. correlated to the post-carburization microstructural parameters	Highly correlated post-cold-forming parameters	Standardized regression coefficient	R²
Average grain size number of the surrounding γ coarse grains (No. 4 and below)	Variation in the α grain size	-1.09	0.70
	Average α grain size number	-0.43	
Area ratio of crystals with an γ grain size number ≥ 10 near the C Segregation	Carburization temperature	-0.60	0.55
	Average α grain size number	-0.49	
	Variation of α grain size	-0.35	
Distance to C segregation in the maximum γ grain	C segregation deformation angle	1.69	0.34
	C segregation interval	-0.47	
Area ratio of crystals with an γ grain size number < 5 near the C segregation	C segregation deformation angle	0.70	0.30
	Carburization temperature	0.54	
	C Segregation interval	-0.36	

6.1.3 Relationship between the parameters after cold forming and the material microstructures and manufacturing parameters (STEP 3)

Among the parameters extracted in Section 6.1.2, those exhibiting a strong correlation with the post-cold-forming parameters were the α grain size No. of the material and its variation, width and interval of the C segregation, and shear strain (Table 5).

In STEP 3, the parameters associated with grain boundary energy and strain energy correlated with the post-cold-forming parameters influencing G.G., consistent with the findings in STEP 2.

Table 5 Relationship between parameters after cold forming and material microstructure and manufacturing condition parameters

Parameters after cold forming	**Highly correlated material factors**	**Standardized regression coefficient**	**R^2**
α grain size after cold forming	α grain size of the material	0.82	0.67
C Segregation interval after cold forming	C segregation interval in the material	0.30	0.30
Variation in the α grain size after cold forming	Variation in the α grain size of material	0.52	0.29
	C segregation width of material	-0.55	
Deformation angle of C segregation after cold forming	Shear strain	0.55	0.31
	C segregation width of material	0.18	
Shear energy	Shear strain	0.61	0.39
	C segregation width of material	0.33	
Carburization temperature	Carburization temperature	-	-

6.2 Relationship between G.G. and the manufacturing parameters that can be controlled (STEP 4)

Based on the microstructural analysis detailed in Section 6.1, the relationship between G.G. and the carburization temperature was examined by incorporating the temperature into the parameters extracted in Section 6.1.3. Consequently, the hierarchy of influence on G.G. was identified as α grain size No. > variation of the material α grain size No. > C segregation width > carburization temperature > shear strain (Table 6).

These results confirm that the occurrence of G.G. is influenced by grain boundary energy (material microstructure), strain energy (cold-forming conditions), and thermal energy (carburization temperature).

Table 6 Relationship between G.G., material structure and manufacturing parameters

Objective variable name	R^2
Maximum γ grain size number	0.21
Variable name	Standardized regression coefficient
Material α grain size number	-0.72
Variation σ in the α grain size	-0.53
Width of C segregation in the material	0.43
Carburization temperature	-0.35
Shear strain	-0.34

7. Discussion

Among the parameters controllable within the manufacturing process, the α grain size No. (α grain size) of the material exhibited a high correlation with G.G. This relationship is speculated to result from the following phenomena:

[1] When the α grain size No. is large (indicating a fine α grain size), the resulting γ grain size following phase transformation is also fine. Therefore, even a minor differential in grain size promotes G.G. due to the high associated grain boundary energy.

[2] Finer grain sizes generally increase material strength and decrease deformation performance during forming. Therefore, when a material with fine grains, which is inherently more resistant to deformation, is cold-formed, a strain differential arises between the local fine-grained microstructure and the other regions in the microstructure, thereby promoting and G.G. This phenomenon is analogous to that described in Section 4.5.

Conversely, parameters related to precipitates were not identified as significant factors influencing G.G. in STEP 1 shown in Fig. 1 (Table 3). This may occur because, in cold-formed components subjected to substantial plastic deformation, the driving force promoting G.G. is more dominant than the inhibition energy provided by precipitates.

In this study, controllable parameters with significant impacts on G.G. were identified by evaluating the causal relationships with intermediate parameters in a stepwise manner, as shown in Fig. 8. However, the direct relationship between these identified parameters and G.G. exhibited a very weak correlation, as shown in Fig. 9 (results in Section 6.2, Fig. 10).

It is posited that this weak correlation stems from the omission of the causal relationships between the intermediate factors shown in Fig. 8. Therefore, in phenomena involving multiple microstructural transformations, the relationships between parameters at each stage must be considered to accurately predict the final microstructure.

As shown in Fig. 11, G.G. occasionally occurred under low-strain conditions rather than high cold-strain conditions, despite identical material properties and carburization temperatures. In this study, all relationships between parameters were modeled as linear; consequently, parameters characterized by nonlinear relationships, such as those indicated by the dashed lines in Fig. 12, were not extracted as highly important parameters. This likely explains why certain observed phenomena could not be elucidated solely through the identified parameters.

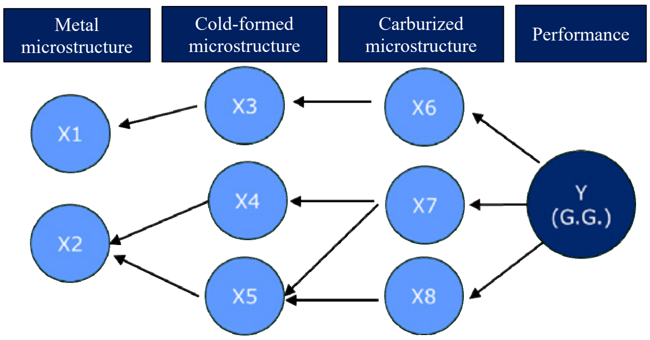


Fig. 8 Method for identifying the influencing factors

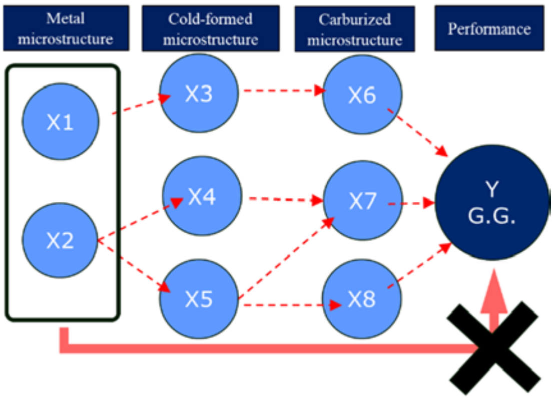


Fig. 9 Method for predicting the G.G.

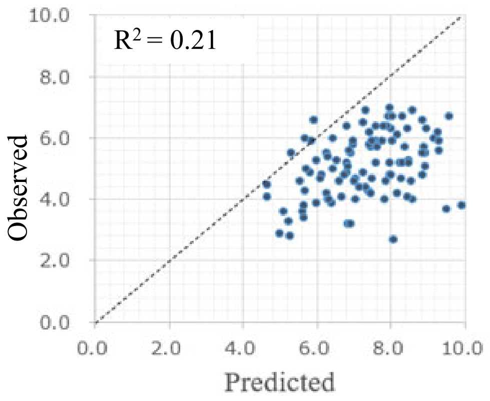


Fig. 10 Multivariate analysis results using material microstructure and manufacturing condition parameters (STEP 4)

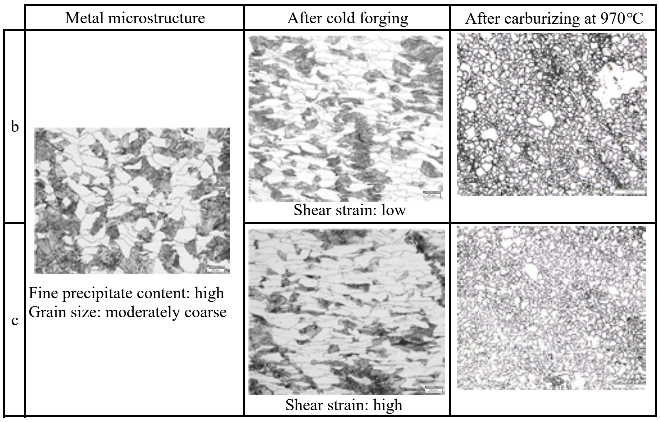


Fig. 11 Comparison of the pre- and post-carburization microstructures

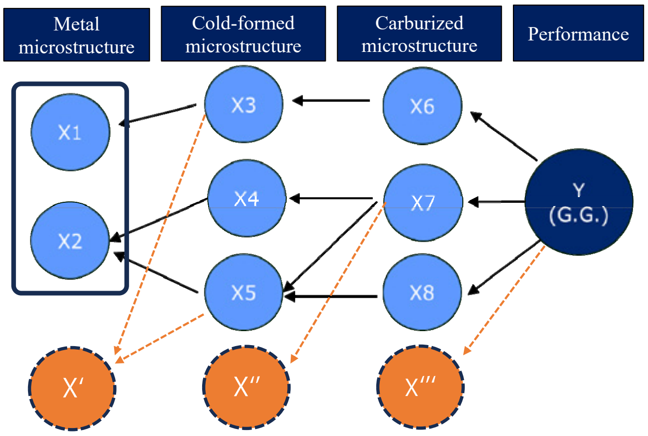


Fig. 12 Issues in the current influencing factor identification approach

8. Conclusion

The following findings were established in this study:

[1] The parameters affecting controllable G.G. within the component manufacturing process were extracted, and their respective degrees of impact were elucidated.

[2] The hierarchy of influence of the controllable influential parameters on G.G. was α grain size No. > variation in the α grain size No. > C segregation width > carburization temperature > shear strain.

[3] Examination of the direct relationship between the controllable parameters and G.G. revealed a weak correlation. This is attributed to the fact that G.G. involves a sequence of repeated microstructural transformations; consequently, correlations are significantly stronger when intermediate parameters and the synergistic combinations of parameters influencing these changes are considered.

9. References

(1) Yasuo Ito, Go Kato and Makoto Maeda: Quantification of the Influence of Factors on Abnormal Austenite Grain Growth in Carburized Steel Parts for Drivetrain, Proceedings of the 2025 Spring Meeting, The Society of Automotive Engineers of Japan, 2025, pp. 1–5, reprinted with permission.

(2) Tatsumi Urita, Kunio Namiki and Tomohito Iikubo: Electric Steelmaking, 59, 1, 33.

(3) Takeshi Fujimatsu, Morihiko Nakazaki, Shinji Fukumoto and Atsushi Yamamoto: Iron and Steel, Vol. 95 (2009), No. 2.

(4) Takeshi Fujimatsu and Kazuya Hashimoto: Sanyo Technical Report, Vol. 17 (2010), No. 1.

(5) Manabu Kubota and Tatsuro Ochi: Nippon Steel Technical Review, 378 (2003), 72.

(6) Naohide Kamiya, Yuki Tanaka and Ryohei Ishikura: DENKI-SEIKO, 89 (2018), 1.

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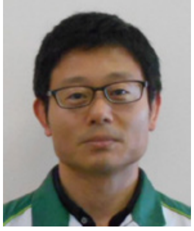

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