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Laser welding of cast iron and carburized steel for differential gear †

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Abstract

This study concerned laser welding replacing the traditional bolted connection of the ring gear and differential case in the power train of the automobile. Laser welding is necessary to reduce weight and manufacturing cost, since the bolted connection method requires additional parts and space. In the differential gear, however, it is difficult to control the welding processes because cast iron and carburized steel contain high carbon content. To solve these welding problems, laser welding using Ni-base filler metal was used in this work. The results of welding with Ni-base filler metal satisfied the torsional stiffness and durability, but compared to the bolted connection method, noise and hardness problems occurred. Therefore, to solve these problems, penetration depth was decrease from 5mm to 4mm and the carburized layer of the ring gear was cut with 1mm. As well, numerical method was used to evaluate welding deformation, torsional stiffness and fatigue.

Keywords: Carburized steel; Cast iron; Computer simulation; Differential gear; Laser welding

1. Introduction

The differential gear is a functional component of the automobile power train and is composed of the differential case and ring gear. Differential gear compensates the trace difference between in-corner wheel and out-corner wheel, while an automobile turns a corner, and enables normal driving [1]. The power train of the automobile delivers engine power to the automobile wheel. Due to this property, it should have good torsional stiffness, wear resistance and fatigue strength. Since cast iron can satisfy these requirements and has low material cost as well as excellent castability, it is widely used for the differential case of a power train. Carburized steel is also used for the ring gear of a power train. However, since these two base materials contain high carbon content, the weldability is not good [2]. In case of cast iron, because of inherent brittleness of the cast iron and the effect of weld thermal cycle on the metallurgical structure of the cast iron, it is difficult to be welded [3]. Hence, the differential gear assembly has been produced by the bolted connection method to join the differential case and ring gears. This method, however, has limits such as it needs additional assembly part, unnecessary flange is required to secure space for the bolted connection, and holes fabrication process is required before bolting process. A bolted connection method is disadvantageous for the reduction of material costs and for the increasing of the production efficiency [4, 5].

Lately, many European automotive companies have tried to use laser welding to join the sheet metals. Generally, Arc welding processes and oxyacetylene welding are the most two common welding processes which are applied to cast iron welding [6-8]. Recently, the application of diffusion bonding, friction welding and electron beam welding are studied by some researchers [9-12]. In this study, however, laser welding was applied to join cast iron and carburized steel due to the properties of laser welding [13, 14]. Also, to solve unweldability for these high carbon steels, the suppressing method of the carbon diffusion is used by controlling cooling speed throughout pre-heat or post-heat treatment. The other method is to use filler metal to reduce the crack or lack of tensile strength which happens during welding [14-16].

In this study, laser welding method was investigated in order to substitute the bolted connection method for the differential gear assembly. Various prototypes were fabricated to compare with the conventional differential gear by bolted connection. The laser welding using Ni base filler metal was applied and numerical analysis was done to evaluate welding deformation, torsional stiffness and fatigue. Also, hardness test, fatigue test, torsional stiffness test, and NVH test were conducted.

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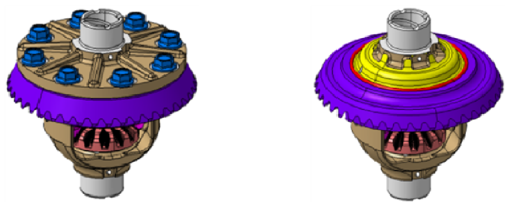
Table 1. Chemical composition of the GCD 500 (wt%).

P	S	C	Si	Mn	Mg
≤0.8	≤0.02	≤2.5	≤2.7	≤0.4	≤0.09

Table 2. Butt welding conditions of GCD500.

Material	Laser power (kW)	Welding speed (m/min)	Focal position (mm)
GCD500	3	1.0	0
GCD500	4	1.2	0
GCD500	5	1.4	0
GCD500	6	1.6	0



(a) Bolted connection (b) Laser welding

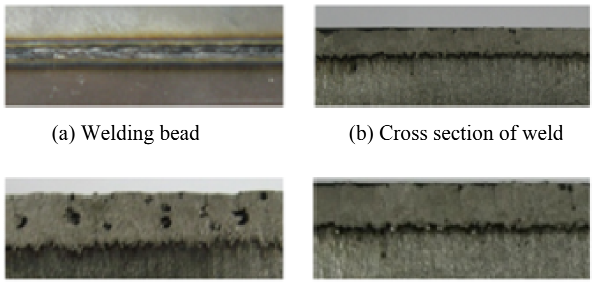
Fig. 1. Structures of bolted connection and laser welding.

Table 3. Chemical composition of SCM420H (wt%).

	P	S	C	Si	Mn
SCM 420H	≤0.03	≤0.03	0.17 ~ 0.23	0.15 ~ 0.35	0.55 ~ 0.90

Table 4. Chemical composition of the filler wire (wt%).

Filler wire	Contents		
	Ni	Mn	Fe
MSG NiFe2(KW-M82)	55.0	3.5	Balance



(a) Welding bead (b) Cross section of weld

(c) Void in weld (d) Crack in weld

Fig. 2. Weld shapes after welding process.

2. Experiments for the welding of the differential gear

2.1 Weldability test of the cast iron

In this study, the material used for the differential case is GCD500 (cast iron) and it has high torsional strength, high wear resistance and high fatigue limits. For these reason, GCD500 is widely used for the power train components. The ring gear also requires high wear resistance and fatigue strength. Also, milling must be needed, therefore SCM420H (carburized steel) is used, which is low carbon steel for machining and carburized after machining to increase wear resistance and fatigue strength. Currently the joining method for the differential case and ring gears relies on the mechanical fastening method by bolting. In case of welding as the joining method, it is hard to achieve weldability, because of cracks, which happen by the martensite and ledeburite structure at the welded zone and carbon alloy metals which have hard and high brittle property is created at partial mixing zone. The martensite structure is created at the heat affected zone of the weld because of high carbon content of the base material. Fig. 1 is a schematic of structure by bolted connection and laser welding.

First, to understand the laser welding property of the GCD500, butt joint welding was done using CO_2 laser. The chemical composition of the GCD500 is shown in Table 1. The test specimen had 10 mm-thickness , 80 mm-width and 180 mm-length. Welding surface was milled for the butt joint welding. To reduce the influence of the plasma which happens during CO_2 laser welding, mixture of helium and argon gas with ratio 1:1 was used as the shielding gas. Also, it was supplied with 20 l/min flow discharge. The welding conditions were used to obtain the penetration which was greater than 4 mm, adjusting the welding speed and laser output power. The welding conditions used in these experiments are shown in Table 2.

It is shown in Fig. 2 that cracks and voids are found on the welding zone. Therefore two sheet metals were not joined completely.

2.2 Methods for better weldability of the GCD500

There are two methods to improve weldability of GCD500. The first one is to interrupt growth of martensite or cementite structure during welding by using Ni-filler metal which is a stabilizing element for austenite. The second one is to suppress carbon diffusion which happens during welding for the high carbon base material by controlling cooling rate throughout pre-heat or post-heat treatment. Then the growth of martensite or cementite which has high brittleness is to be decreased. Unfortunately, heating control process is not adequate because of its additional high cost equipment and time consumption. Thus, the method of adding the Ni-filler metal was chosen in this work.

To find the effect of the Ni-filler metal, butt welding tests with GCD500 and carburized steel SCM420H were done by using filler wire feeding method applied to CO_2 laser welding. The chemical compositions for SCM420H are shown in Table 3. The geometry of test specimen has 5 mm-thickness, 80 mm-width and 180 mm-length. Groove surface was milled to depth 4 mm with angle 12 degree. The chemical compositions of the filler metal are shown in Table 4.

To reduce the plasma effect, mixture of helium and argon

Table 5. Welding test results for GCD500 and carburized steel.

Filler metal	Specimen	Welding speed (m/min)	Max load (N)	Tensile strength (MPa)
Without Ni-filler metal	GCD500-GCD500	1.2	0	0
	GCD500-GCD500	1.4	0	0
	GCD500-GCD500	1.6	0	0
Ni-filler added	GCD500-GCD500	1.2	6733	168
	GCD500-GCD500	1.4	5866	146
	GCD500-GCD500	1.6	4949	124
Without Ni-filler metal	GCD500-SCM420H	1.2	14667	366
	GCD500-SCM420H	1.4	13950	349
	GCD500-SCM420H	1.6	13255	331
Ni-filler added	GCD500-SCM420H	1.2	18536	463
	GCD500-SCM420H	1.4	17781	444
	GCD500-SCM420H	1.6	16834	420

was supplied with a flow rate 20 l/min. Among welding conditions, only welding speed is altered as shown in Table 5, and penetration depth and laser power are fixed to 4 mm and 4 kW. Tensile tests and micro-structure analysis were performed to know the effect of Ni-filler metal. The specimen for tensile test was machined according to KS-B-0801 specification and tensile testing speed was set to 15 mm/min. Also, micro defects such as crack and porosity were found after etching with 3% nitral acid. Tensile test results are shown in Table 5 for GCD500 and SCM420H.

According to the welding test, welding defects which happened for the GCD500 similar metal welding and incompleteness of a welding which were due to the cracks were solved by using Ni-filler metal and the welding quality was improved. It also shows that the tensile strength was increased more than about 100 MPa in case for using Ni-filler metal than not using Ni-filler metal from the welding test for the dissimilar metals between the cast iron and carburized steel. Also through the sectional analysis, it showed that porosities which existed when not using filler metal were eliminated when using filler metal.

3. Fabrication of the prototype and perform the verification test

3.1 Fabrication of the prototypes

To verify the preceding tests, three different kinds of prototypes, A-type, B-type, and C-type were fabricated, and welding experiments were done with the same conditions as the preceding tests. 4kW CO_2 laser was used with Ni-based filler wire. The gear and case were fitted with pressing. Since it needs lead time for the laser power to reach the set value, the welding was performed with 400° circumferentially rotating for the stability. The geometry of the prototypes and groove shapes are as follows in Table 6. Welding conditions are shown in Table 7 for each prototype respectively. Groove surface was milled to depth 4 mm with angle 12 degree.

Table 6. Structures of three prototypes.

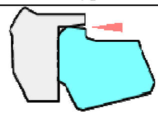
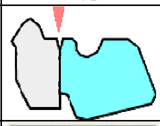
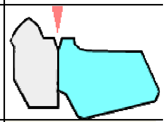
Type		A-type	B-type	C-type
Cross section				
Part	Gear			
	Case			
Assembly				

Table 7. Welding conditions for each prototype.

Type	Penetration depth (mm)	Laser power (kW)	Welding speed (m/min)	Focal position (mm)	Shielding gas
A-type	5	5	2.25	2	He
B-type	5	5	2.25	2	He
C-type	5	5	2.25	2	He

Table 8. Maximum hardness for weld of three prototypes.

Type	A-type	B-type	C-type
Hardness of ring-gear HAZ (Hv)	730.6	717.3	765.8

3.2 Laser welding of the prototypes

To evaluate the samples which were joined by the laser welding, the hardness of the welded zone was measured. Table 8 shows the maximum hardness of weld for each type. It can be found that the hardness of B-type is smaller than any other types. However, unfortunately micro-cracks are found near heat affected zone for all types as shown in Table 9.

Torsional stiffness and fatigue test for each type are shown in Table 10. To compare the results by laser welding with that by bolted connection, torsional stiffness, fatigue, and noise test

Table 9. Analysis of cross section of three prototypes.

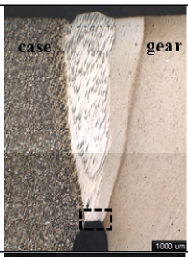
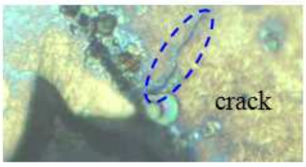
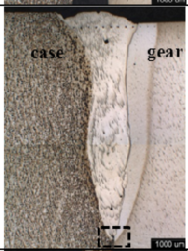
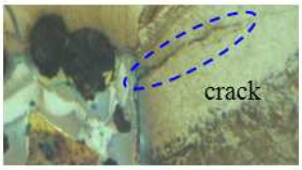
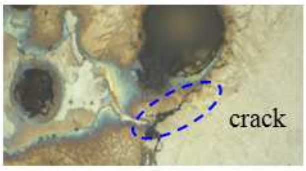
Type	Cross section	Crack occurrence
A-type		
B-type		
C-type		

Table 10. Torsional stiffness and fatigue test.

	Bolted connection	A-type	B-type	C-type
Torsional stiffness (Nm/rad)	1850	2103	2146	2153
Fatigue test (cycle)	500000	500000		

were performed. It can be found in Table 10 that the torsional stiffness by laser welding are greater than that by bolting process and also durability (fatigue test) is satisfied.

Table 11 shows the results of noises measured for each type of the structures. It shows that the performance of the conventional structure by bolted connection is superior or equivalent to the structure of laser welding, with respect to noise test.

4. Numerical analysis and experiment for the modified prototypes

4.1 Modified prototypes

To understand the cause of the noises, the height deviations (Δh) at gear area were measured and the results are shown in Table 12. The distortions were found at the gear zone and these were caused by the residual stresses during circumferential laser welding. And these distortions were considered to be the cause of noise.

Table 11. Noise measurement for prototypes (dB).

	Bolted connection	A-type	B-type	C-type
Acceleration	76	76	76	75.5
Deceleration	67.4	67.4	70.9	67.9

Table 12. Measurement result for the height deviation at gear area.

Sample	A-type	B-type	C-type
Δh (mm)	-0.02~ 0.03	-0.15~ 0.10	-0.12~ 0.10

Table 13. Maximum height deviation at gear area (mm).

Penetration depth	A'-type (Modified A-type)	B'-type (Modified B-type)	C'-type (Modified C-type)
5 mm	0.0014	0.0570	0.025
4 mm	0.00044	0.044	0.0133

Also, it can be found that the cause of the high hardness at the HAZ of the ring gears was because of the fast diffusion of carbon by the laser welding. To solve the high hardness problem at HAZ of the ring gear and welding deformation problem as mentioned above, the welding penetration depth was to be changed from 5mm to 4mm and the angle of groove was to be change from 12 degree to 16 degree. The reduction of penetration depth decreased the welding heat input and welding deformation which cause the noise problem. Also, thickness 1 mm of the gear surface nearby the welding area was removed and this removed thickness is equivalent to an effective cast depth for the surface carburizing.

4.2 Welding simulation for the modified prototypes

Since time consumption and high cost were necessary to perform experimentally and computer simulations were used. SYSWELD is commercially available software for welding phenomena and heat treatment. This software was used to evaluate the effect of the reduced penetration depth and removal of the carburization layer. The stress concentration phenomenon was simulated by using NX_NASTRAN, commercially available software for structure analysis, to predict the stiffness and strength according to the change of the weld penetration depth. The torsional stiffness and fatigue life was simulated by using FEMFAT which is commercially available software for fatigue analysis.

Table 13 is the results of height deviations at gear area, by finite element method with respect to the depth of penetration for each prototype, respectively. From this numerical analysis, it was found that the reduction of penetration influences on the decreasing the deformation. For A'-type, the deformation reduction ratio is 69% at the highest deformed region. As shown in Fig. 3, the deformation for A'-type (modified A-type) is remarkably smaller than those for B'-type (modified B-type) and C'-type (modified C-type).

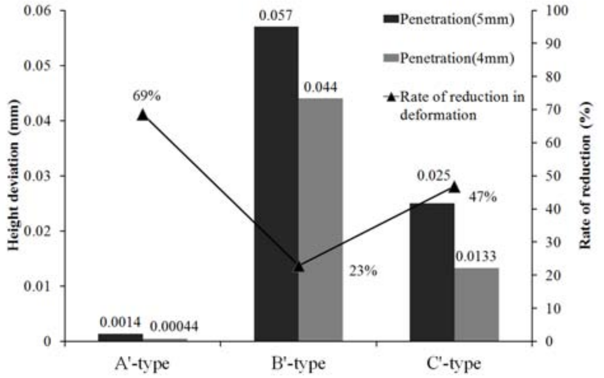
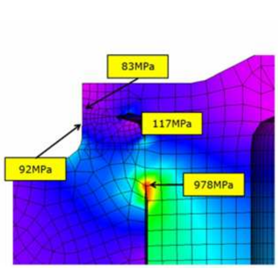
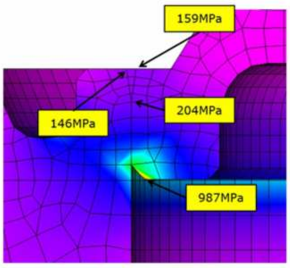


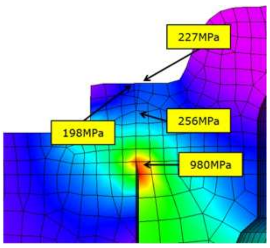
Fig. 3. Deformation reduction ratio according to the change of the weld penetration depth.



(a) A'-type



(b) B'-type



(c) C'-type

Fig. 4. Simulation results of torsional stress.

When the penetration was changed, it was seen that there was no big difference for the stress distribution by simulation with SYSWELD. It was predicted that there would be nearly no problems for the decreasing stress by the change of the penetration depth. However, to predict the torsional stress decrease and fatigue problem according to the change of penetration depth, the torsional stress and fatigue life was simulated by using NX_NASTRAN.

Stress distributions were obtained by NX_NASTRAN with the case fixed and 8000N-m of torque was applied at the bottom of gear. Fig. 4 shows the simulation results of torsional stress. The torsional stress was affected little by the change of the weld penetration depth because same level stress was distributed regardless of the weld penetration depth. The maximum stress load was at the differential case than the welding area. This means that welding area would be relatively safer than the base material. Also, by comparing stress distribution under same torque, the A'-type was the safest type and then C'-type and B'-type in sequence.

Table 14. Welding conditions per structure of the modified prototypes.

	Welding depth (mm)	Laser power (kW)	Welding speed (m/min)	Focal position (mm)
A'-type	4	4.5	2.9	2
C'-type	4	4.5	2.25	2

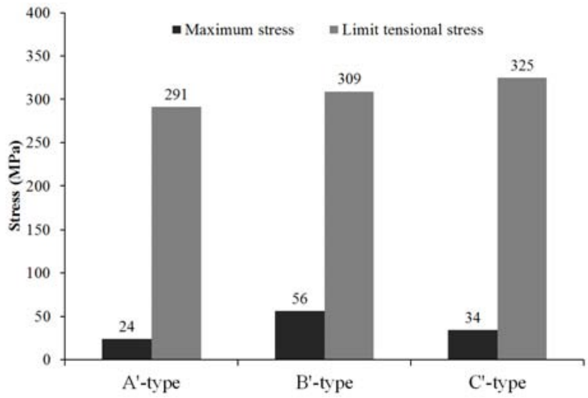


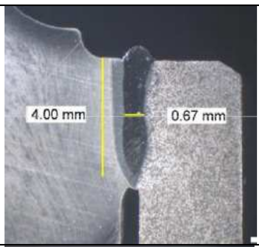
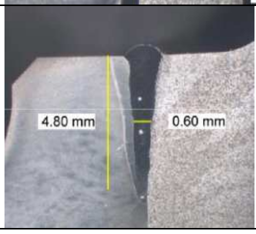
Fig. 5. Simulation result for fatigue analysis.

FEMFAT was used to find fatigue strength according to the change of the structure. The fatigue analysis was conducted with 2700N-m torque and more than 1,000,000 cycles. As a boundary condition, residual stress acquired by SYSWELD simulation and torsional stress acquired by NX_NASTRAN were applied. Fig. 5 is the simulation result of a fatigue analysis for each modified type. It is shown that the maximum stress of all the A'-type, B'-type, and C'-type has approximate 1/7~1/10 of the limit tensional stress. This means that it has infinite fatigue life cycle. Also, among 3 types, A'-type had the most excellent result with 1973000 cycles.

4.3 Welding test for the modified prototypes

Through previous simulation results, it was probable that the structure of modified prototypes could solve welding deformation problems. Welding tests were done by fabricating modified prototypes and the welding results were evaluated with torsion, durability (fatigue test) and NVH tests like same case as previous prototypes. The CO_2 laser using filler wire feeding method was applied in the same way as previous prototype tests. The gear and case were fitted with pressing and the joint region aligned to the laser beam and specimen rotating method was used. However, because the penetration depth was decreased, the laser power was decreased from 5 kW to 4.5 kW. For the A'-type, vertical holding jig was used during welding. Welding speed was increased from 2.25 m/min to 2.9 m/min. Table 14 indicates the modified welding conditions. However, in the case for the B'-type, according to the simulation results and prototype test, the deformation result was most severe and weight reducing effect was most minimal

Table 15. Cross sections of the modified prototypes.

	Cross section	Crack
A'-type		
C'-type		

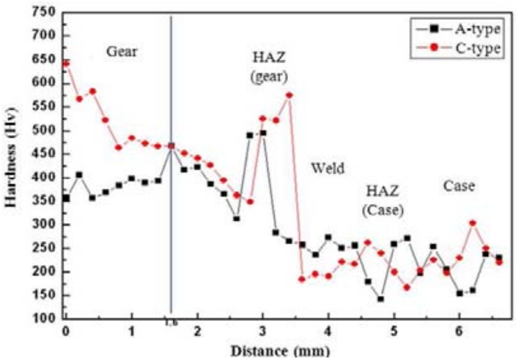


Fig. 6. Hardness distribution at weld of the modified prototypes.

among A'-type, B'-type and C'-type prototypes. Therefore, the B'-type was excluded for the modified prototype welding test considering cost and time saving wise.

4.4 Weldability of the modified prototypes

Hardness of weld was analyzed by cutting a section of modified specimen made by laser welding. Vickers hardness was measured with the 200 g load, 10 sec duration time, 200 μm test interval. Fig. 6 shows the result of hardness measured for modified prototypes.

As a result of hardness testing, it was revealed that hardness of HAZ of ring gear is under 480 Hv in case of A'-type, and is under 600 Hv in case of C'-type. This means that high hardness problem at HAZ of the gear was solved. Table 15 is the results of the welding sectional analysis of the modified prototypes. As the result from the sectional analysis, micro cracks under 30 μm which happened at the weld was also removed.

Through the results of simulations and hardness measurements, the modified prototype of A'-type has exceptionally excellent results compared to the modified prototype of C'-type. Finally A'-type differential gear was selected as final applicable structure. To evaluate further mechanical performance of A'-type, torsional stiffness, durability (fatigue) and noise level tests were done.

Table 16. Torsional stiffness, fatigue, and NVH test for the modified prototypes.

		Bolted connection	Welding-type (modified A-type)
Torsional stiffness (Nm/rad)		1773~1913	2153~2192
Fatigue life (Cycle)		500000	500000
NVH test	Acceleration (dB)	76	76
	Negative accelera-tion (dB)	67.4	65.6

Table 16 is the result of torsional stiffness, fatigue, and NVH tests for the modified prototype. From the test result, the prototype joined by welding (modified A-type) by laser welding had higher torsional stiffness value than the gear by bolting. And it was evaluated that it had same level of fatigue life with the differential gear by bolting, because the fatigue test for the part passed the standard evaluations, 500000 cycles. For the noise level test during acceleration and deceleration, it also had the equivalent level of quality with the differential gear by bolting. Proceeding from what has been said above, it should be concluded that the modified A-type (A'-type) has better performance than the conventional structure by bolting.

5. Conclusions

This study has shown that the laser welding method using Ni-filler metal is capable of replacing the traditional bolted connection of the ring gear and differential case in the differential gear. Three kinds of prototype were fabricated and their torsional stiffness, fatigue, and noise properties were evaluated in order to compare their performance with the conventional bolted connection structure. The three prototypes had equivalent level of torsional stiffness, fatigue properties compared to the structure by bolted connection, but they had high hardness and noise problem because of welding deformation. Penetration depth was decrease from 5 mm to 4 mm to solve welding deformation problem by high heat input. Also, the carburized layer of the ring gear was cut with 1 mm in order to reduce hardness level. By applying the numerical analysis and performing laser welding and weldability tests to these three kinds of modified prototype, it was shown that the integrated type differential gear joined by laser welding has better performance than the conventional differential gear joined by bolting method. This work has demonstrated the possibility that the laser welding method could substitute the conventional bolted connection method in the joining process of the ring gear and differential case.

Acknowledgment

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