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Radial forging of aluminum to steel preform for the production of light-weighted wheel bearing outer race

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Abstract

In this research work an innovative procedure through which to manufacture the outer race of vehicles wheels bearing, aiming to reduce their total weight, is proposed. Utilizing the radial forging process, an aluminum workpiece is forged on a steel core, resulting in the same geometry for the wheel bearing outer race but allowing to achieve a considerable weight reduction. By considering the most burdensome load conditions the outer race has to stand, a stress analysis is implemented in ABAQUS/Standard by applying both bolts and bearing ball forces. Based on the stress distribution, the portion of the cross-section where the load is bearable by the aluminum 6061 alloy is identified and a new steel workpiece, realized by removing the above-mentioned volume, is created. The aluminum workpiece is then hot-forged on the steel part, replacing the removed steel volume and recreating the original shape of the bearing outer race, afterwards tested with the same load conditions to verify that the combined forged part is able to withstand the same loads. To optimize the interface behavior between hot-forged Al6061 and 45Cr steel, simple tension test specimens, realized by forging an aluminum workpiece on a steel plate, have been manufactured realizing different surface knurling on the steel plate and by pre-heating the aluminum part at different temperatures. With the proposed approach, the weight of the bearing outer race has been reduced of 35.8% while granting the same mechanical performances of the original component.

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Keywords: Radial forging; Combined forging; Two-materials forging; Light-weight wheel bearing; FE simulation

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1. Introduction

In today's world, vehicle fuel efficiency is growing in importance due to increasing concerns about fuel shortage and environmental impact of exhaust gas. Combustion engine technology has greatly improved in the last decades but, being already a century-old invention, its small progresses seem not to be aligned with the pressing demand for enhancing vehicles overall efficiency. For this reason, the research focus should move to different components where improvements are still possible. To this aim, the utilization of lightweight materials have always played an important role in reducing the overall weight of vehicles but, in some cases, the complete substitution of a standard component with one realized utilizing lighter materials is not feasible. This impossibility is mainly related to the generally lower mechanical properties of light-weight material compared with standard ones. However, if a combination of lightweight and high mechanical performances materials is utilized for the production of the same component, the advantages of both materials can be exploited, allowing to realize a lighter product which shares the same performances with the original one. Concerning the available technologies for the joining of dissimilar materials, an important recent work is due to Martinsen et al. [1] the available technologies for joining dissimilar materials are summarized ad reviewed, highlighting pros-and-cons of their utilization. Furthermore, one of the key-aspects of the combined utilization of high mechanical properties and lightweight material is represented by the performances of the resulting joining area and, about this topic, some authors spent some effort, as follows. Seitz et al [2] studied the feasibility of utilizing a double material preform in the ring rolling process in order to exploit the combined mechanical properties of two different materials, highlighting however that the simple flat surface contact does not meet the requirements for the joining strength. Huang et al. [3] studied a joining process including both heat and plastic deformation in order to join thin layers of dissimilar materials, studying the influence of the process parameters on the quality of the joining area. Lazarevic et al. [4] studied the joining of dissimilar materials in the friction stir forming, highlighting how innovative tool design can effectively increase the joining strength. Finally, Jafarlou et al. [5] studied the improvement in the joining strength of parts made by joining steel and aluminum where an Ag-Cu-Sn interlayer was placed, showing how it can improve the overall mechanical properties of the resulting part. In the present research work, an innovative way to fabricate wheel bearings outer race is proposed by means of combined radial forging of an aluminum workpiece on a steel preform. In order to improve the joining strength between steel and aluminum, a knurling surface has been realized on the steel preform. The joining strength has been tested by means of laboratory experiment where both knurling geometry and process conditions have been varied in order to identify the best combination to maximize the joining strength. The results of the FEM simulation will show how the combined forged product is able to withstand the load conditions of the original one while granting a considerable weight reduction.

2. Material characterization

In order to properly characterize the behavior of both 45Cr steel and 6061 aluminum alloy, to be used in the numerical simulations, compression tests have been carried out on cylindrical specimens by utilizing the Singang SGA-HC-1MN test machine. Both aluminum and steel compression test specimens have been realized with an Ø30mm diameter and a 40mm height. For the 45Cr steel, tests have been carried out at 25°C, 150°C, 250°C, 350°C and 450°C and under $0.01s^{-1}$, $0.1s^{-1}$ and $1\ s^{-1}$ strain rates whereas, for the 6061 alloy, 250°C, 300°C, 400°C and 450°C and $0.01s^{-1}$, $0.1s^{-1}$ and $1.0\ s^{-1}$ strain rates have been tested, respectively. The results of the compression tests have been fitted utilizing the Johnson-Cook model, Eq. (1), and the model constants, for both materials, are reported in Table 1.

$$\sigma = \left(\boldsymbol{A} + \boldsymbol{B}\varepsilon^{\boldsymbol{n}}\right)\left(1 + \boldsymbol{C}\ln\left(\frac{\varepsilon}{\varepsilon_{ref}}\right)\right)\left(1 - \left(\frac{\boldsymbol{T} - \boldsymbol{T}_{ref}}{\boldsymbol{T}_{melt} - \boldsymbol{T}_{ref}}\right)^{\boldsymbol{m}}\right) \tag{1}$$

Table 1. Johnson-Cook model constant for the 45Cr steel and for the 6061 aluminum alloy

Material	A	B	C	n	m
45Cr steel	325.202	284.806	0.4061	0.01576	0.4843
6061 alloy	324.012	113.856	0.4215	0.0027	1.3432

In order to determine the combination of temperature and surface knurling on the steel part that assures the best joining strength between steel and aluminum, laboratory experiments have been carried out by upsetting an aluminum workpiece on steel parts with different surface knurling, Fig. 1. For the knurling shown in Fig. 1b, Fig. 1c and Fig. 1d, both depth and width of the grove are equal to 1mm and have been all realized by means of milling process. Each knurling presents a different pitch, 1.0mm, 1.5mm and 2.0mm, as shown in Fig. 2b, 2c and 2d, respectively.

As first, the three knurling type specimens have been manufactured considering the lower extremum of the hot forging temperature range for the 6061 aluminum alloy, namely 375°C. Afterwards, considering the promising results of the type "2" knurling, additional experiments have been carried out considering a higher temperature, close to the middle point of the 6061 alloy hot forging temperature range, as well as testing the influence of a continuous pressure on the specimen for 30s after the complete upsetting. The experiments have been repeated three times for each one of the knurling-temperatures combinations shown in Table 2, observing a maximum error below 5% on the maximum value of the joining strength curve.

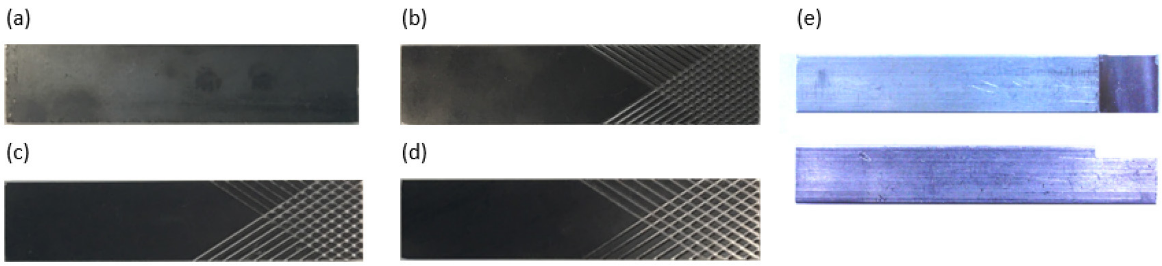


Fig. 1. (a) Flat surface, (b) knurling type "1", (c) knurling type "2", (d) knurling type "3" and (e) aluminum specimen

Table 2. Knurling parameters and specimen realization process conditions

Case	Knurling type	Steel temperature [°C]	Al temperature [°C]	Upsetting die speed [mm/s]	Post-pressure and cooling	Preliminary result
1	-	300	375	0.5	Instant air cooling	Failed to join
2	1	300	375	0.5	Instant air cooling	Joined
3	2	300	375	0.5	Instant air cooling	Joined
4	2	300	425	0.5	Instant air cooling	Joined
5	2	300	375	0.5	30s post-pressure	Joined
6	2	300	425	0.5	30s post-pressure	Joined
7	3	300	375	0.5	Instant air cooling	Joined

For the manufacturing of the two-material simple tension test specimens, the SGA-HC-1MN Singang Precision Ind. compression machine has been utilized. The steel specimen has been positioned on the bottom support plate of the machine and, on its top, the aluminum workpiece has been placed. In the upsetting operation, the height of the aluminum workpiece has been reduced of 50% and the resulting specimen is shown in Fig. 2a, top view, and Fig. 2b, side view. In all the three types of knurling, the aluminum is seen to flow well on the sides of the steel grooves, filling completely the gaps, as shown in Fig. 2c, where the cut cross-section of the knurling type 1, 2 and 3 are presented.

The upsetting machine, with the specimens on the die, and the results of the simple tension test operated on the six cases shown in Table 2, in terms of eng. stress-strain curves, are reported in Fig. 3a and 3b, respectively. Case 6 has been identified as the best combination of temperature and steel surface knurling which assures the highest joining strength between the two materials, namely 68 MPa. This combination of knurling and temperatures, relevant for Case 6, has been utilized on the steel preform used in the radial forging simulation, presented in the following section 3. All the specimens with knurling have shown the same typology of failure, characterized by a detachment of the aluminum part from the steel, as shown in Fig. 3c for the type "2" knurling. Furthermore, although also the Case 1 (flat surface) has been tested, the results of the adhesion was not satisfactory thus the results has not been included in the paper.

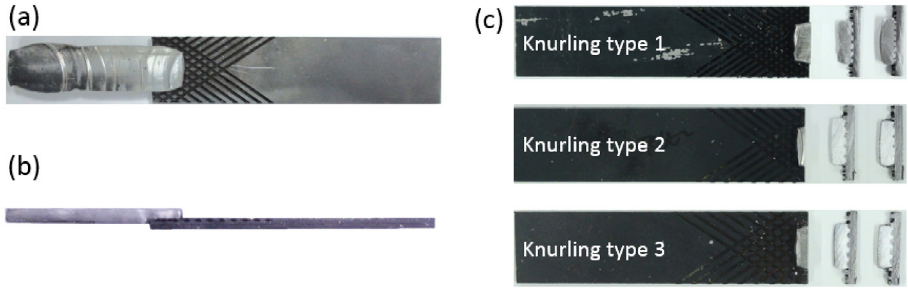


Fig. 2. (a), (b) Steel-6061 Al forged simple tension test specimen and (c) section of the joining area for the three different knurling

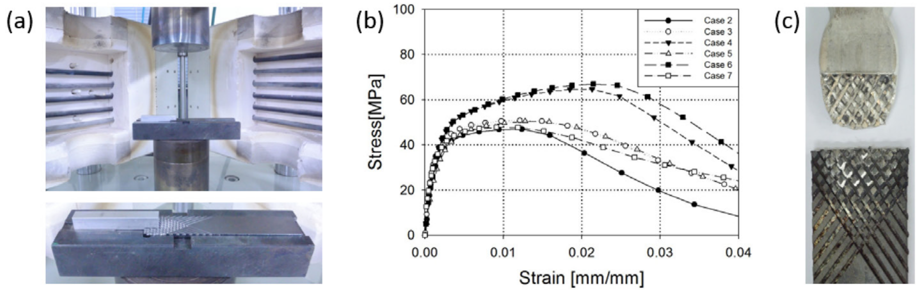
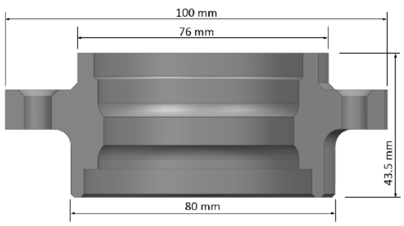


Fig. 3. (a) Specimen upsetting process, (b) Eng. stress-strain curves (cases shown in Table 2) and (c) specimen surface after failure

3. Calculation procedure, numerical implementation and results

The proposed approach for substituting part of the original steel material of the outer race of an automotive wheel bearing, whose cross-section dimensions are shown in Fig. 4, is subdivided into three different steps. In the first step, by simulating the most burdensome stress conditions for the component, the stress distribution in the cross-section is calculated. Afterward, by considering the yield strength of the 6061 aluminum alloy and taking into account the threshold given by the maximum joining strength calculated in the previous paragraph, the portion of the cross-section, suitable to be realized by aluminum, is identified. The remaining portion of the outer bearing shall be realized with the original steel. By utilizing the radial forging process, a ring-shaped aluminum workpiece is forged on the steel preform, filling the portion of the cross-section where the steel was previously removed and allowing to create a shape similar to that of the original bearing, without the bolt holes, but with a considerable reduction of its weight.

Differently compared with the standard radial forging process, where the workpiece is put into rotation by a mandrel inserted inside it or where the part itself is put into rotation by additional dies, in the radial forging process utilized for the manufacturing of the proposed two-material bearing, Fig. 7, the four radial dies move both in the circumferential direction, with a rotation span of ±45°, as well as toward the aluminum workpiece, making it to attach to the steel part as well as to rise up and go down to recreate both flange and walls of the original part. The bolt holes, as well as the original narrowing, not includable in the radial forging process, must be create in a post-operation machining phase. In order to ensure that the two-material outer race is able to bear the same load condition of the steel one, and that the stress field in the joining area is below the threshold joining value, a second stress analysis, with the same load conditions of the initial one, is carried out and the results, in terms of radial and shear stress, are presented in this paragraph. Both stress analysis, on the full steel bearing and on the aluminum-steel bearing, have been implemented in ABAQUS/Static. By taking into account that the considered wheel bearing is normally installed on commercial vehicles, whose weight can be averagely assumed to be 2000kg, the resulting load for each bearing is 500kg. The load has been subdivide on the 43 nodes surrounding the bolt holes, resulting in a local force of 116.3N for each node. Based on the distance between the balls and the bolt holes, a reaction force for each of the balls has been calculated in 456.2N, subdivided on the 9 nodes surrounding the ideal contact point between the ball itself and the inner surface of the bearing, resulting in a radial force of 50.7N for each nodes. The load boundary conditions are shown in Fig. 5. In the two material outer bearing, the application of the bolt forces will results in a shearing load transfer between the aluminum outer part and the steel inner one hence, the joining strength tests, presented in the previous paragraph, provide a reasonable reference value to be used as threshold for the estimation of the portion of the cross-section which can be manufactured with aluminum without compromising the mechanical properties of the component. Hence, from the results of the von Mises equivalent stress in the cross-section of the bearing, and by taking into account the threshold given by the joining strength presented in the previous paragraph, the area meant to be replaced with aluminum is also identified as the zone on the left of the red-dashed line in Fig. 6. Accordingly, the remaining portion of the bearing, on the right of the red-dashed line in Fig. 6, represents the steel preform and shall be realized with the original 45Cr material.



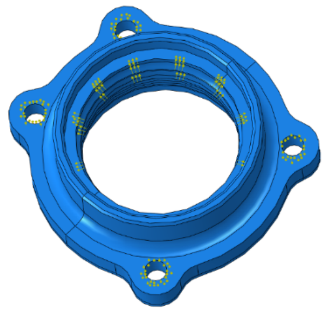
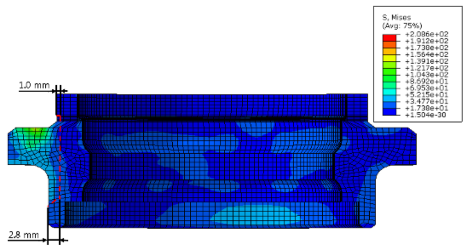
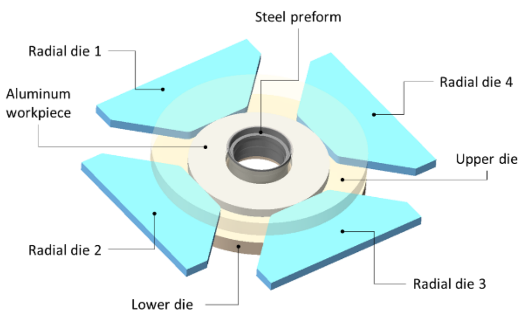



Fig. 4. Dimension of the considered wheel bearing; Fig. 5. Load boundary conditions in the ABAQUS stress analysis; Fig. 6. Stress field in the cross section of the steel bearing;

By means of radial forging process, the aluminum preform, with a volume equal to the 120% or the removed steel, and with inner diameter, outer diameter and height equal to 80mm, 170mm and 12mm, respectively, has been forged on the steel preform. The simulation has been implemented in ABAQUS/Explicit considering a steel temperature of 300°C, same as the tools temperature, and an initial temperature for the aluminum workpiece equal to 425°C. In order to avoid excessive deformations on the steel part, two pins have been inserted from both top and bottom of the inner hole. Tools have been modeled as rigid with heat transfer and both the aluminum workpiece and the steel preform have been modeled with C3D8R hexahedral elements of 2.5mm and 3mm side, respectively. The initial stage is shown in Fig. 8 whereas the final shape, Fig. 9, has been obtained after a total of 10 consecutive deformations of the radial dies on the aluminum workpiece, after which the outer diameter of the aluminum workpiece has been reduced to 140mm, allowing to obtain a shape comparable to that of the original full-steel bearing.



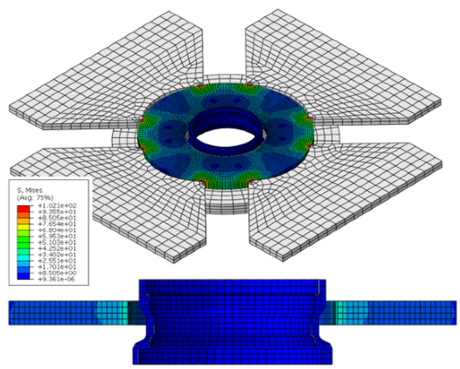
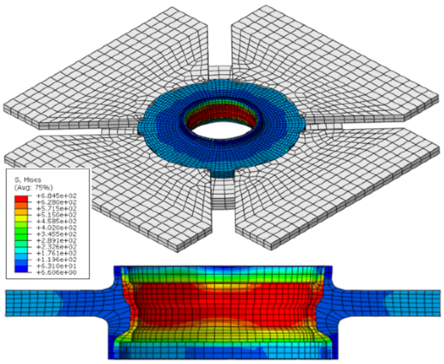


Fig. 7. Schematic representation of the radial forging process; Fig. 8. Radial forging initial state, isometric and cross-section views.

Both steel preform and aluminum-forged part meshes have been exported and imported in ABAQUS/Static for the stress analysis verification, with the same load conditions applied in the previous case but considering a joining strength between aluminum and steel. The joining strength between steel and aluminum has been calculated considering the geometry of the knurling and the pattern repetition in the overlapping area between the two materials, resulting in 68MPa (Case 6 in Table 2 and Fig. 3b). The cross-section of the combined-forged part, as inputted in the ABAQUS/Static stress simulation, is shown in Fig. 9. The application of the same loading conditions on the two-materials bearing results in a stress field in the cross-section which never exceed the joining strength limit of 68MPa, neither in the normal component nor in the shear one, proving that the aluminum-steel bearing is able to withstand the same load conditions of the original, as shown in Fig. 10.



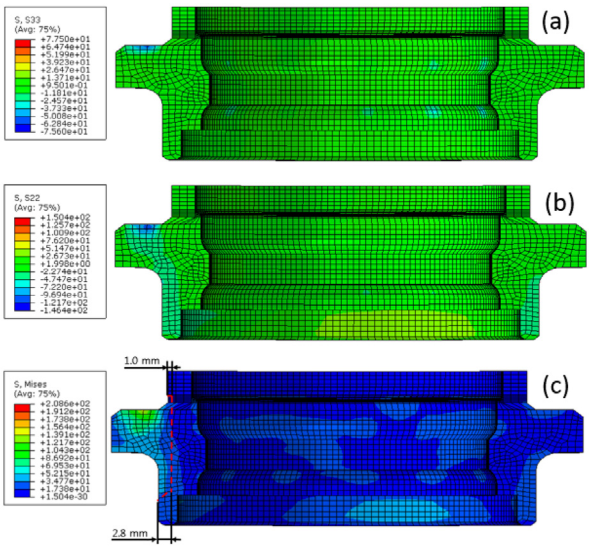


Fig. 9. Radial forging final state, isometric and cross-section views; Fig. 10. Combined forged Al-steel bearing (a) normal, (b) shear and (c) von Mises equivalent stress field in the cross-section

4. Conclusion and future work

In the present research work an innovative approach for the lightweight oriented redesign of the outer race of automotive wheel bearings is proposed and the stages to follow for its implementation are detailed. Based on the results of the study case selected for this preliminary fundamental investigation, the weight of this component of the wheel bearing assembly can be reduced of 35.8% compared to its original weight. Considering that in each commercial vehicle four bearing systems are installed, one for each wheel, the proposed methodology pursue the weight reduction aim for the future vehicles. Furthermore, although the radial forging process is a well-established manufacturing process, its utilization for the hot forging of an aluminum workpiece on a steel preform should be further studied for a proper optimization of the tool geometries, in order to reduce the undesired spread of the material between the tools.

In addition, more detailed study and experimental verifications on the combined forged part are planned to be carried out in order to analyze all the aspects of the in-operation of bearing, namely dynamic loading and well as wear, for a successful industrial transfer of this new-developed technology.

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