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Application of Cold Expansion on Different Materials: A Review

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Cold expansion or cold-hole expansion is one of the mechanical surface treatment methods applied to circular holes of engineering structures for improved service performance. The main mechanism is to induce non-homogenous plastic deformation by oversized mandrels or balls leading to beneficial compressive residual stress fields and hardness increase around the applied holes. Cold expansion is an important method to enhance fatigue life of particularly lightweight materials and components in aviation industry. In addition, to aluminium and titanium alloys, different materials such as steels were also treated *via* cold expansion for fatigue life improvement. In this paper, characteristics of different methods used in cold expansion were introduced/reviewed in detail. In addition, the review was presented according to application of cold expansion to different materials. Readers can navigate to materials of interest and find previous studies conducted on the same and/or similar materials. Therefore, this review shows a new direction along with an established process that has not been investigated before.

Keywords: Cold expansion, hole edge expansion, direct mandrel expansion, ball expansion, split sleeve expansion, residual stress, fatigue

1. INTRODUCTION

Service performance of engineering components is very critical in terms of structural integrity. Parameters such as design, operating conditions and microstructural characteristics have an impact on final service life. Due to

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demanding performance requirements in industries such as aerospace and automotive, special surface treatments are applied to improve surface characteristics of materials for better performance. As a result of inducing compressive residual stress fields, hardness increase and microstructural modifications, resistance to failure mechanisms such as fatigue, stress corrosion cracking and wear can be improved. Mechanical surface treatments such as cold expansion, shot peening, laser peening and flapper peening are widely preferred methods to enhance service life of engineering components in aerospace and automotive industry.

Fatigue has detrimental effects on structural integrity of engineering components and is the main failure mechanism of engineering structures such as aircrafts [1]. Mechanical surface treatment methods such as cold expansion, shot peening and laser peening can be used to improve service performance of engineering components without any change in material type or design [2]. Owing to application of these surface treatments to susceptible-to-failure locations, local fatigue resistance can be improved significantly. One of the widely used mechanical surface treatment methods, shot peening employs ceramic or steel medium impacting on surface with a certain selected velocity [3]. Compressive residual stresses near surface layer and increase in hardness of applied materials can be achieved. However, surface roughness is also increased after shot peening, leading to increase in crack initiation sites. Laser peening introduces deeper compressive residual stresses with better surface profile compared to shot peening. However, application of laser peening to inside of cylindrical parts or deep holes with small diameter is challenging.

Cold expansion, widely used in aerospace industry, is a mechanical surface treatment method applied to circular holes for fatigue life improvement [4]. The main mechanism of this method is based on non-homogenous plastic deformation of hole edges to induce beneficial compressive residual stresses. Owing to beneficial residual stress fields, fatigue crack initiation and propagation can be delayed or even suppressed by application of this method. Compared to other mechanical surface treatment techniques such as shot peening and laser peening, this method is well-suited for edges or inside of the circular deep holes.

Due to higher stress intensity factor under loading, hole edges and adjacent regions are more susceptible to crack initiation and propagation leading to premature failures. For instance, fastener holes, which are geometrical discontinuities in structure of airplanes, can act as a stress concentrator under load and fatigue cracking can be observed initiating around fastener holes. Fatigue failures arising around the fastener holes are responsible for 50-90% of fractures of aging planes [5], as in the case of Aloha Airlines, Flight 243 [6], was one of the shocking incident in the aviation history.

In this review, cold expansion process was investigated in details. Different approaches used in the open literature were studied. In addition, the review was conducted based on the applied material. Readers can navigate to materials of interest and find previous studies conducted on the same and/or similar materials. Therefore, this review shows a new direction along with an established process that has not been investigated before.

2. METHODS OF COLD EXPANSION

There are different techniques for cold expansion used over the last decades such as mandrel expansion, split sleeve expansion and sleeveless expansion. [7,8]. All the methods are designed to induce plastic deformation of circular holes of components by using a harder tool compared to material to be processed. During removal of tool from circular hole, circumferential compressive residual stresses are generated [7]. Due to production history, there can be pre-cold expansion residual stresses either tensile or compressive. During the application of mandrel or ball, the hole is expanded so that tensile hoop stress or tangential stresses close to yield stress of the material can be generated. After the tool is removed, compressive residual stresses are formed owing to plastic deformation and spring-back effect [8]. A typical hoop stresses or tangential stress distribution after cold expansion can be seen in Figure 1. A significant compressive residual stress field, acting

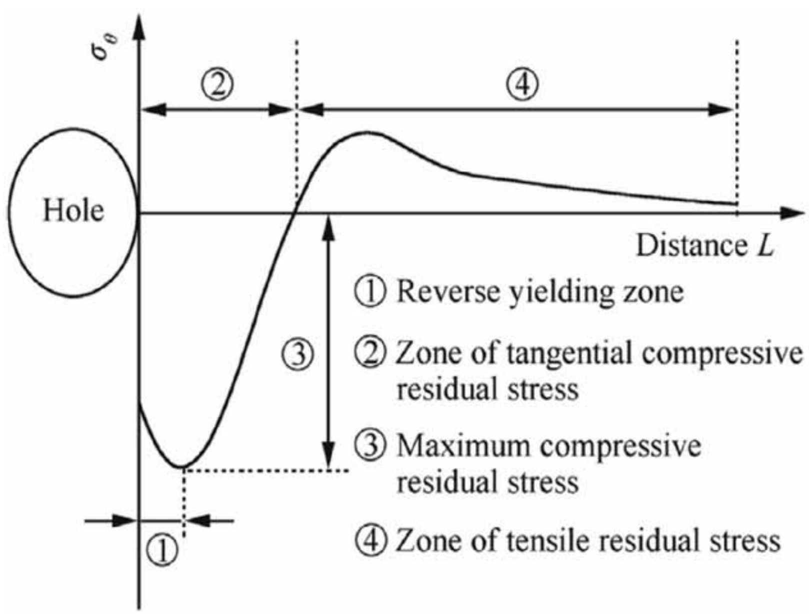

FIGURE 1
A schematic of compressive residual stress generation during cold expansion for tangential or hoop stress [8].

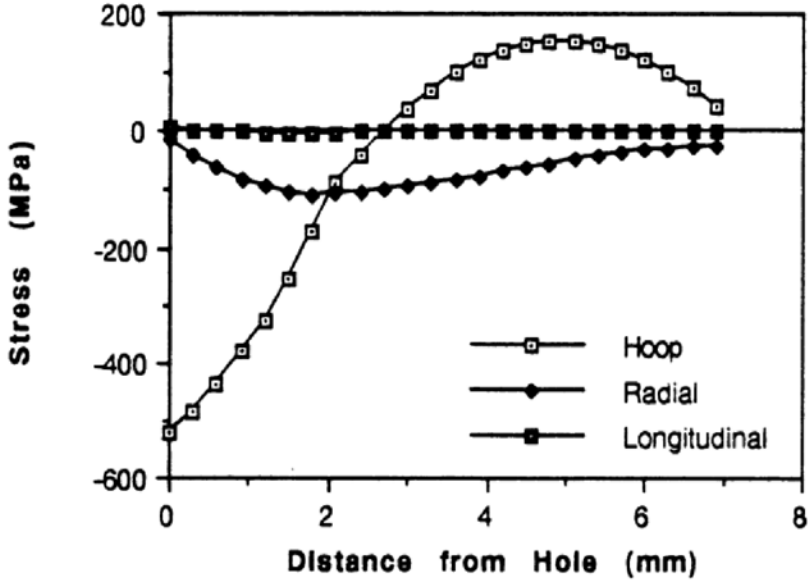

FIGURE 2
Measured residual stress profiles after cold expansion [7].

against crack initiation and propagation, is introduced after non-homogenous plastic deformation. Balancing tensile residual stresses are also inherently formed through the depth for the hoop stresses, as shown in Figure 1. Residual stress profiles after cold expansion, measured by employing Sach's Method can be seen in Figure 2. Compressive residual stresses around the holes can delay initiation and also propagation of fatigue cracks by reducing the stress intensity factor around holes. Owing to residual stress profiles obtained in Figure 2, significant fatigue life improvement was observed particularly at low and intermediate stress levels for 7050 aluminium alloy as can be seen Figure 3.

Although the main mechanism for fatigue life improvement is the same, there are different methods of cold expansion technique. According to literature review most preferred methods for cold expansion are: hole edge expansion, direct mandrel expansion, ball expansion and split sleeve expansion processes [8,9]. Different methods of cold expansion surface treatment are summarised in Table 1.

2.1. Hole edge expansion

Hole edge expansion is performed by hardened percussion tool with tapered indenter (Figure 4). In this method, only edges of holes are treated so that very limit area is plastically deformed. Therefore, the effective region is smaller compared to the other cold expansion methods. On the other hand,

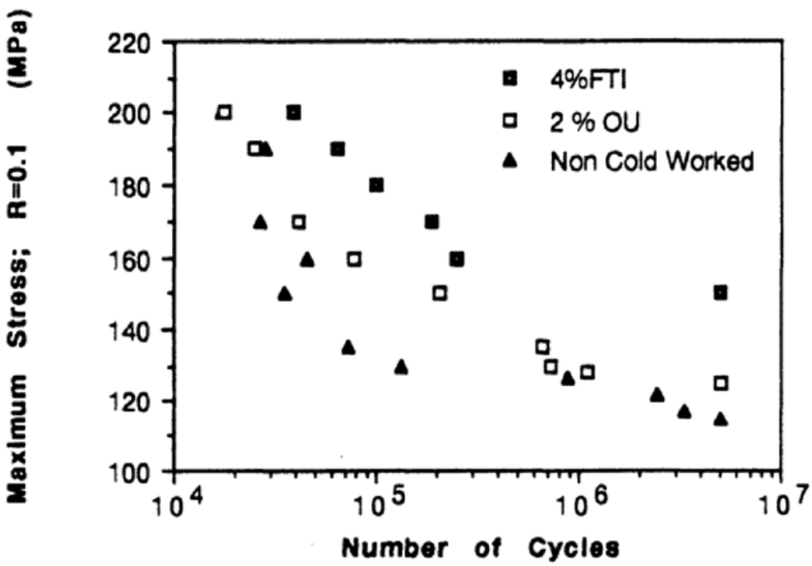

FIGURE 3
Fatigue life improvement after cold expansion owing to compressive residual stresses in hoop direction as given in Figure 2 [7].

TABLE 1
Comparison of cold expansion methods

Cold Expansion Techniques	Application Area	Advantage	Disadvantage
Hole Expansion	Hole edges	Simple and relatively fast	Smaller region is affected
Direct Mandrel	Whole inner surface	Better fatigue life improvement than ball expansion method	Misalignment of mandrel can disturb residual stress distribution
Ball Expansion	Whole inner surface	Applicable on hard materials	Weak points at the entrance and exit of specimen
Split Sleeve Expansion	Whole inner surface	Very limited surface damage	More process time is required
Sleeveless Split Mandrel	Whole inner surface	Faster process than split sleeve method	Appropriate lubrication is needed

application of hole edge expansion method is simple and can be applied consecutive times to obtain desired performance improvement. In literature, this method is also called as hammer peening [8]. According to study of Liu et al., fivefold fatigue life enhancement was achieved by use of this method for 2A12-T4 aluminium sheets [10].

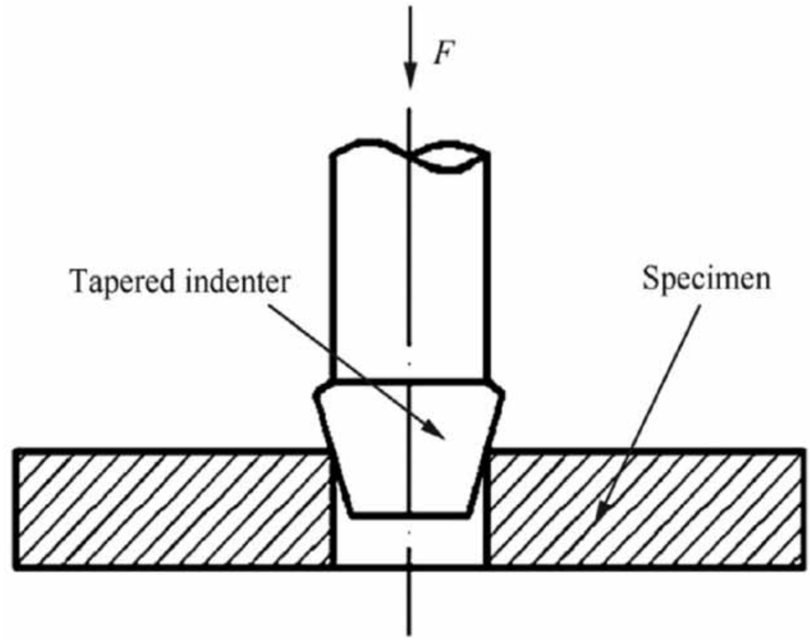

FIGURE 4
A schematic of hole edge expansion method [8].

2.2. Direct mandrel expansion

Direct mandrel expansion is performed by conical pin as shown in Figure 5. Compared to hole edge expansion method, oversized lubricated mandrel is pushed inside the hole so that through-thickness surface alteration can be obtained. There are many parameters affecting the efficiency of hole expansion, such as lubrication, expansion degree, mandrel speed, hole size [11-13]. In addition, orientation of mandrel has significant effect on the uniformity of the hardness increase and residual stress generation. If the axis of the alignment of mandrel is not fully vertical with respect to hole, distribution of residual stresses around hole will be non-axisymmetric after cold expansion [14]. This situation can generate weak points which allow fatigue cracks to initiate and grow. In order to eliminate this problem, double cold expansion is suggested to be applied [15]. However, depending on the orientation of mandrel, non-axisymmetric residual stress fields can be observed despite application of double cold expansion.

2.3. Ball expansion

In ball expansion, an oversized ball goes through the hole to obtain plastic deformation leading to residual stress generation and hardness increase [16]. Compared to Direct Mandrel Expansion, harder materials can be processes by this method owing to lower friction forces between contact sur-

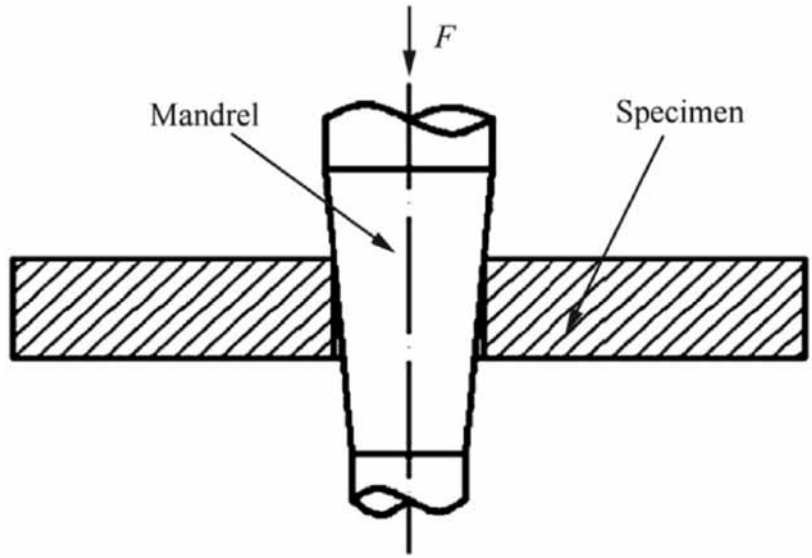

FIGURE 5
A schematic of direct mandrel expansion method [8].

faces (Figure 6). In addition, there is no indents on the material because of formation of a natural hydrodynamic wedge between workpiece and tool. Thus, this method can be used in steel plates [8,17].

Compared to mandrel expansion methods, ball expansion leads to limited improvement on fatigue life. In the literature, it was stated that after ball expansion, tensile stresses were obtained at the entrance and exit face of hole. On the other hand, it was claimed that tensile stress was only observed on exit of hole in mandrel methods [15]. As a result, depending on the process parameters, limited improvement or even reduction in fatigue life can be observed if the balancing tensile residual stresses are obtained at critical locations.

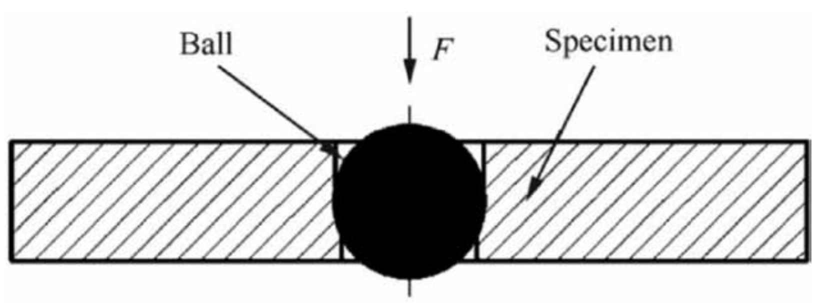

FIGURE 6
A schematic of ball expansion [8].

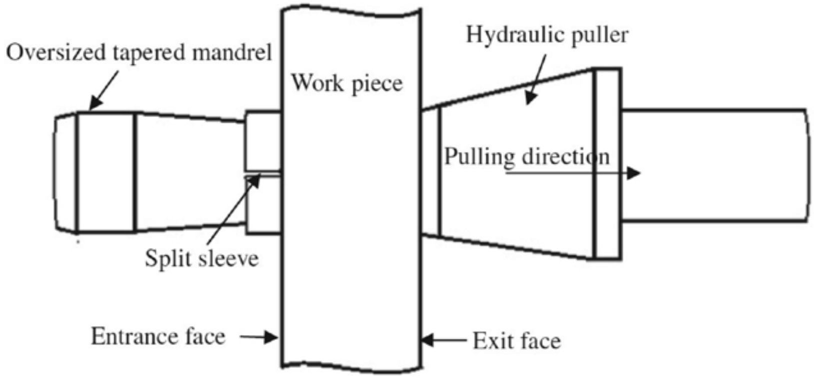

FIGURE 7
A schematic of split sleeve expansion [19].

2.4. Split sleeve expansion

Split sleeve cold expansion technique was developed by Boeing in early 1970s [18]. In this method, residual stresses are generated by pulling oversized mandrel through split sleeve (Figure 7). Split sleeve is used to avoid damaging surface of holes due to high friction caused by high interference [19]. On the other hand, cracking can occur during expansion process because of geometry of sleeve [20]

In split sleeve process, mandrel with sleeve is pushed into the hole. Mandrel is drawn back through the sleeve and sleeve expands the hole [21]. After that, sleeve is removed from the hole (Figure 8).

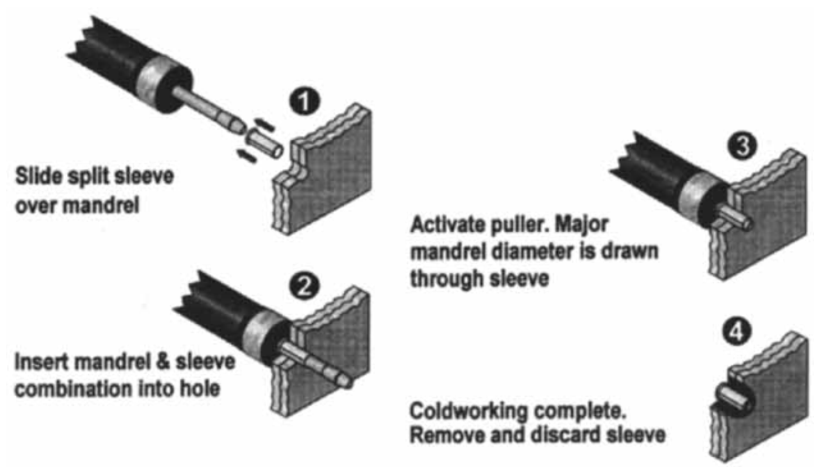

FIGURE 8
Process of split sleeve expansion with sleeve [21].

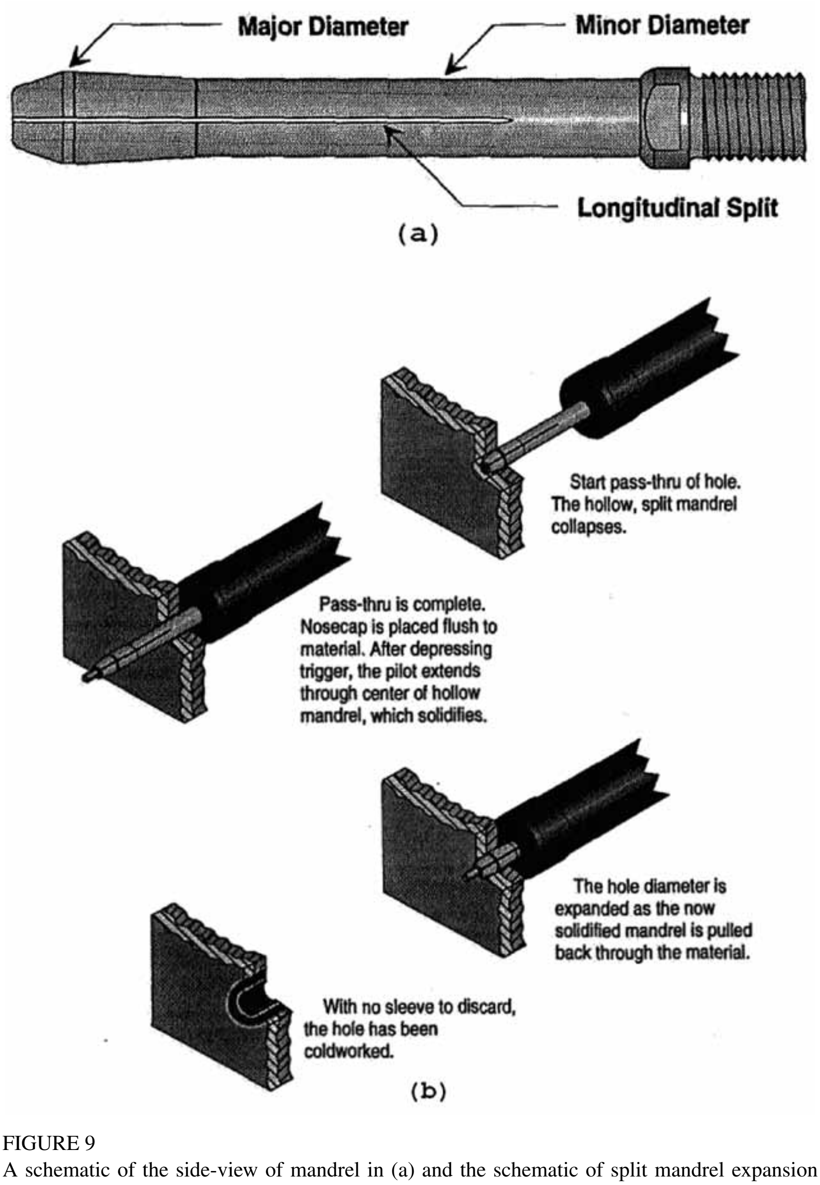

FIGURE 9
A schematic of the side-view of mandrel in (a) and the schematic of split mandrel expansion without sleeve in (b) [22].

Due to process time of sleeve application, Boeing developed sleeveless split mandrel method in 1980 [21]. Instead of split sleeve, mandrel with longitudinally slot is used as can be seen in Figure 9. Longitudinally slot allows mandrel to collapse during pulling process into hole. However, this method requires appropriate lubrication because of lack of sleeve [22]. Otherwise, soft materials can be damaged during the application of sleeveless split mandrel method.

3. APPLICATIONS IN DIFFERENT MATERIALS

Cold expansion method is used mostly in aviation industry [8,18]. The main reason is to increase fatigue resistance of holes, particularly rivet holes, number of which is very high in aircrafts. Therefore, many examples of application on light metals including aluminium alloys can be found in literature [8]. On the other hand, studies related to harder materials are limited in the open literature. There are very few articles on the investigation of fatigue behaviour of titanium alloys and steels after cold expansion. In addition, there are also studies about developing of a new model for analytical prediction and simulate the different conditions [23-30]. As a result of experimental studies, simple and realistic models were developed to predict fatigue crack growth [31]. Effects of cold expansion on different materials was summarized in Table 2.

3.1. Aluminium Alloys

Considering cold expansion studies in the open literature, aluminium alloys are the most widely investigated material. Owing to use in aerospace and automotive industry, aluminium alloys were preferred in the studies. Mostefa et al. performed ball expansion on 6082-T6 aluminium alloys to compare results of tests with stress model calculated by Miner's rule under changing

TABLE 2
Effect of cold expansion to fatigue performance of different materials.

Material	Method	Improvement of Fatigue life	Reference
2024-T3	Split sleeve with taper pin Split sleeve with ball	5.3x 1.8x	[23]
6061-T6	Ball expansion	2x	[4]
7085-T7651	Split sleeve and SWCW	1.7-47x	[33]
7050-T7451	Split sleeve and SWCW	1.3-45x	[33]
2A12T4	Direct Mandrel	6x	[14]
7075-T651	Direct Mandrel	2x	[11]
7475-T7351	Split sleeve	1.5-3.2x	[39]
TC4	Split sleeve	1.5-3x	[19]
TC4	Split sleeve	1.7-2.2x	[41]
30CrMnSiNi2A	Direct Mandrel	1.21x	[43]
1020	Split sleeve	1.5-7x	[45]
AZ31B	Split sleeve	3x	[47]

load sequence. It was found that experimental service life was lower compared to prediction of Miner's rule and it was argued that load sequence had a minor effect on crack initiation [32].

Edwards and Ozdemir analysed fatigue life of 5.0 mm-thick 7050 plate with sleeveless cold expansion and compared with commercial split sleeve method [7]. They found that although both methods led to improvement, fatigue life after split sleeve process was higher, which was incorporated with higher compressive residual stress fields.

In another study, Easterbrook and Landy developed a new process called Stress Wave Cold Working (SWCW) and compared with split sleeve cold expansion [33]. It was claimed that the new process generated beneficial residual compressive stresses around the hole and through thickness of the part before hole drilling. According to test results of 7085-T7651 and 7050-T7451 plates, SWCW led to fatigue life improvement greater than split sleeve cold working ranging from over 1.5 to 12 times.

Viveros et al. investigated fatigue crack growth in welds of 6061-T6 samples after cold expansion [4]. According to experimental results, cold expansion with 4.1% expansion rate increased fatigue life of 6061-T6 aluminium alloy, but it was ineffective for weld metal and heat affected zone specimens.

Kawdi and Shanmukh performed a stress analysis for 7050 during split sleeve process with FEM [34]. This analysis showed that a significant fatigue life improvement could be obtained with split sleeve cold expansion after a period of constant amplitude.

Shahriary and Chakherlou studied the effect of cold expansion on fretting fatigue life of 2024-T3 plates [35]. According to their results, high expansion rates of cold expansion process had no significant effect on fretting fatigue life. In addition, it was discussed that geometrical distortion could be observed due to high expansion rate. It was also stated to fully benefit from bolt clamping and cold expansion, the plate deformation should be reduced during the cold expansion process by using sleeve.

Liu et al. investigated residual stress distribution of 2A12T4 [14]. After series of fatigue tests, it was found that fatigue life increases six times with direct cold expansion technique.

Baltach et al. performed numerical study to analyse the effect of mandrel shape on residual stress around the hole of 7075-T6 plate [15]. In this study, ball and conical mandrel were modelled with different taper angle. It was found that conical mandrel was more suitable for the cold expansion, especially for thick plates while ball mandrel generates tensile stress around the hole edge. Moreover, lower taper degree has a positive effect on compressive residual stress at the entrance face of hole.

Su et al. presented both experimental and numerical studies to investigate the effect of the single and double expansion on 6082-T6 [25]. Result of studies showed that double expansion provided better fatigue life and especially double expansion in opposite direction was highly beneficial, because it generated more compressive residual stress at the entrance of the hole.

Kumar et al. investigated effect of cold expansion with rotating mandrel [36]. A 3D thermo-mechanical finite element model was developed to analyse residual stress fields. It was found that the effectiveness of the method relied on friction and plastic deformation between workpiece and mandrel. It was concluded that by employing the optimised parameters, this method could prevent damage in the entry and exit of hole and allow higher degree of cold expansion with nanopowder lubricating.

Gopalakrishna et al. presented experimental results of residual stresses of Al 2024-T3 after split sleeve with taper and ball cold expansion methods [23]. According to this comparative study, split sleeve with taper pin method achieved 200 % higher fatigue life enhancement compared to ball method. It was also found that, residual stresses raised up to 5%-hole expansion rate and decreased for further rate of expansion rate.

Kumar and Babu found out by finite element simulations that fatigue life of 7075-T651 plate could be improved up to 6.6 times with 2% expansion rate [11].

Nigrelli and Pasta performed cold expansion simulation of 5083-H321 aluminium plate by using DEFORM [37]. They found that residual stress could change through the thickness and their analyses showed that the compressive residual stresses increases with increasing plate thickness, because thicker plate provided distributed compressive hoop residual stresses.

Lacarac et al. compared fatigue life of 2024 and 2650 samples before and after cold expansion [38]. They found that cold expanded hole had better fatigue life. However, cold expansion had a slightly effect on fatigue life in surface cracks less than about 1 mm.

Burlat et al. applied cold expansion on the 7475-T7351 samples in different degrees. They found that crack grows rate was higher at the entry face because of low residual stress and at cold expansion degree of 5.58% fatigue life improvement factor is 3.2 [39].

3.2. Titanium Alloys

Titanium alloys are one of the most-widely used materials in aircrafts because of lightweight and better mechanical properties compared to aluminium alloys. Yan et al. investigated fatigue behaviour of TC4 titanium alloy by using split sleeve cold expansion method [19]. It was found that fatigue life of the materials was increased 1.5 – 3.0 times after cold expansion.

In other study, optimization of cold hole expansion of titanium alloys was carried out according to resulting residual stresses [26]. It was shown that application of double cold hole expansion with opposite directions led to more homogenous residual stress fields.

Achard et al. [40] investigated fatigue performance of Ti-6Al-4V under various expansion rates. It was concluded that titanium alloys could withstand up to 8% expansion rates. At 8% expansion rates, tension stresses increased significantly and it was argued that they might cause crack initiation.

Yuan et al. compared Smith-Watson-Topper method with Wang- Brown method to predict fatigue life of TC4 [41]. Based on the results of experimental studies, it was found that Wang – Brown method was more realistic.

3.3. Steels

Maximov et al. studied hardening behaviour of medium carbon steel after cold expansion process [42]. They developed a finite element model to analyse residual stress concentration. Experimental tests were performed to optimize the model.

Su et al. developed a simplified model to estimate fatigue growth behaviour of high strength steel, 30CrMnSiNi2A [43]. By using oversized mandrel fatigue endurance limit was increased 1.21 times. It was seen that there was a good agreement between S-N curves of the model and the experimental results.

In another study, Hacini et al. investigated hammer peening process of 304L plates to optimize process parameters [44]. It was found that surface compressive residual stresses were generated during the first three hammering process. Moreover, hammer peening did not initiate any cracks at the surface of sample.

Stack and Stephens studied fatigue behaviour of 1020 steel by using split sleeve method [45]. They found an improvement in fatigue life. Rather than crack initiation, there was a significant improvement in crack growth stage of the fatigue life. Furthermore, it was concluded that the split-sleeve cold-expansion process had compressive residual stress relaxation under higher stress values, therefore, it had limited advantages for low alloy steels.

Caron et al. applied ball expansion method to a precracked A42 ferritic steel samples to delay further crack growth. Compressive residual stresses were obtained by employing neutron diffraction and FEM. Therefore, it was claimed that ball expansion method could generate compressive residual stresses leading to fatigue life improvement.

3.4. Other Materials

Faghih et al. analysed fatigue behaviour of magnesium sheets after cold expansion [47]. It was shown that split sleeve cold expansion increased the fatigue life of magnesium sheets by delaying crack initiation. Experimental studies were carried out to verify the numerical model. It was found that optimum cold expansion rate for 3.18 mm magnesium sheet was 6%. Higher rate of expansions was claimed to cause micro cracks so that decrease in fatigue life could be expected.

Fatigue Technologies developed GromEx system to improve fatigue life of fastener hole of Carbon Fiber Reinforced Plastics without causing localized damage [48]. During removal of the mandrel, the grommet was expanded radially leading to an increase in fatigue life and protection against lightning strike measured based on sparks observed during testing. Additionally, there was no fastener installation and removal damage on composite.

4. CONCLUSIONS

Cold expansion is one of the mechanical surface treatment methods preferred mainly to enhance fatigue life of lightweight material in aerospace industry. Depending on the application and requirements, different approaches can be applied to achieve service life improvements. In addition, various materials were processes by the cold expansion method to increase mainly fatigue performance.

Based on the open literature, it was found that cold expansion method is mostly applied to aluminium alloys owing to wide usage in aerospace. Application to titanium alloys, steels and other materials were very limited. Depending on service conditions, about 5% expansion rate was declared as the optimum rate to achieve maximum compressive residual stress [49,50]. It was discussed that increase in expansion rate would start to induce microcracking leading to decrease in service life. Fatigue life enhancement was declared as 6-28 times depending on the application configuration [8,11,51,52]. In titanium alloys, fatigue life improvement can be reached up to 3 times [19]. Therefore, it can be concluded that service performance of various materials can be improved by employing cold expansion method. However, numerical and experimental investigations are required to optimize process parameters to maximize performance enhancement.

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